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Potential Reductions of Phosphorus in Urban Watersheds Using a High-Efficiency Street-Cleaning Program, Cambridge, Massachusetts

By Jason R. Sorenson

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
	Volume	
liter (L)	0.2642	gallon (gal)
cubic meter (m^3)	264.2	gallon (gal)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
pounds per curb-mile	3.55	kilograms per curb-kilometer
tons per day (ton/d)	0.9075	metric ton per day

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Vertical coordinate information is referenced to the insert datum name (and abbreviation) here, for instance, “North American Vertical Datum of 1988 (NAVD 88)”

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of chemical constituents in solidsare given either in milligrams per kilogram (mg/kg), or as a percent (%).

Potential Reductions of Phosphorus in Urban Watersheds Using a High-Efficiency Street-Cleaning Program, Cambridge, Massachusetts

By Jason R. Sorenson

Abstract

Material accumulating and washing off onto urban street surfaces and ultimately into public drainage systems represents a substantial non-point source of solids, phosphorus, and other contaminant loading to waterways in urban areas. Cost and lack of usable space limit the type and number of structural stormwater control measures available to municipalities and other public managers. Non-structural measures such as street cleaning are commonly employed by cities and towns for construction, maintenance and esthetics, and may represent a means to reduce contaminant loading to waterways. Effectiveness of street cleaning is highly variable and potential benefits of street-cleaning activities to water quality are not fully understood. The U.S. Geological Survey, in cooperation with the City of Cambridge, Massachusetts, the Massachusetts Department of Environmental Protection, and the U.S. Environmental Protection Agency, conducted a study to better understand the physical and chemical nature of the material on street surfaces, evaluate the performance of a high-efficiency street cleaner, and construct a source loading and management model (SLAMM) to estimate potential

reductions in solids and phosphorus loading to the Lower Charles River from high-efficiency street cleaning.

Street-dirt composite samples were collected from six streets in Cambridge, Massachusetts and the material was separated into three grain-size fractions: (1) greater than 2 mm, (2) less than 2 mm to greater than 125 µm, and (3) less than 125 µm. These data were used to characterize accumulation rates, washoff due to rain events, the removal efficiency of a regenerative-air street cleaner, and concentrations of organic carbon, phosphorus and 31 other trace elements in predominantly high-density/multifamily residential and commercial land-use areas which represent about 42 percent of the total area in the city.

Average yield of material on the street collected between May and December 2010, was found to be about 740 pounds per curb-mile in the multifamily land-use streets and about 522 pounds per curb-mile in the commercial land-use streets. Large amounts of material collected at the end-of-winter in March 2011, which were, about 2,609 and 4,788 pounds per curb-mile for multifamily and commercial land-use types, respectively. Nearly 87 percent of the total yield on all streets was found to be larger than fine sand (>125 microns in diameter). Grain-size distribution were similar within each land-use type. About 32 percent of the total yield from multifamily streets was within the > 2 milimeter fraction, about 54 percent within the < 2 millimeter to >125 micron fraction, and about 14 percent within <125 micron size fraction. Observed grain-sizes from coarse to fine in commercial street-dirt yields were about 19, 67, and 14 percent, respectively. Study street sections ranged from 25 to 43 feet wide. Observations of street-dirt on road surfaces indicate material is well-distributed, showing about 56 percent of the total mass within three feet of the curb, 74 percent within 6 feet of the curb, and 96 percent within 9 feet of the curb.

Acculumation rates of total street-dirt material were similar between both land-use types and ranged from -43 (loss of material) to 308 lbs/curb-mi/day. In terms of grain size, the largest accumulation rates were seen within the less-than-2-mm to greater-than-125-µm fraction. Median accumulations rates observed on multifamily and commercial streets were about 33 and 23 pounds per curb-mile per day, respectively. Results indicate that street dirt in Cambridge, MA can recover to pre-event yields within 5 to 17 days after washoff or street-cleaning events. Median total washoff following rainfall events appears to be nearly the same at about 35 and 40 percent for multifamily and commercial land-use types, respectively. Washoff by grain-size fraction for all streets was found to generally increase with decreasing grain size with the exception of the > 2 mm fraction on multifamily streets, which showed an average net increase of material likely associated with wash-on organic debris from trees, lawns and other plantings more commonly found in residential areas.

The median removal efficiency of total material by a regenerative-air street cleaner was about 85 percent on the multifamily land-use streets and about 79 percent on the commercial land-use streets. Median removal efficiencies increased with increasing grain size fraction and from coarse to fine were about 92, 83, and 53 percent, respectively on multifamily streets and about 92, 79, and 51 percent, respectively on commercial streets. Regardless of the initial street-dirt load, this type of regenerative-air street cleaner left a median residual load on the street surface of about 100 lbs/curb-mi. Ranges of residual loads indicates this machine can begin to removed material at initial street-dirt yields between 18 and 46 lbs/curb-mi.

Median concentrations of organic carbon and phosphorus on multifamily streets were found to be about 35 and 29 percent greater, respectively than those found on commercial streets. Concentrations generally increased with decreasing grain size, except for organic carbon, Ca, K, Mg, P, and Sr, in the grain-size fractions greater than 125 µm within both land-use types. In terms of mass, the median total mass of organic carbon and phosphorus on multifamily streets found to be 68 and 75 percent greater, respectively than those found on commercial streets. About 87 and 75 percent of the mass of phosphorus was found within the two larger grains-size fractions for multifamily and commercial streets, respectively. However, the total phosphorus mass observed within the less than 125 micron fraction on commercial streets was about 47 percent greater than multifamily streets. The median total accumulation rate for total phosphorus on multifamily streets was about 4.0 x 10^{-4} lbs/curb-mi/day and about 5.0 x 10^{-5} lbs/curb-mi/day on commercial streets. The largest phosphorus accumulation rate by grain-size fraction was within the less than 2 mm to greater than 125 µm fraction and was the sme for streets within both land-use types at 0.004 lbs/curb-mi/day. Accumulation rates within the coarsest and finest grain-size fractions on multifamily streets were order of magnitudes greater than those on onserved on commercial streets. Median washoff of phosphorus was similar between multifamily and commercial land-use types for the three grain-size fractions and generall increased with decreasing grain size. Median total washoff of phosphorus was about 59 and 51 percent for multifamily and commercial streets, respectively. However, streets in both land-use types showed wide ranges between -1454 to 96 percent that demonstrate the potential for "wash on" of materials as well as the potential for effective washoff of street materials. Much larger observations of wash-on or net increases of material was seen on multifamily land-use streets. Total phosphorus median reductions for multifamily and commercial streets were about 92 and 81 percent, respectively, and were similar in terms of grain size between both land-use types.

A Source Loading and Management Model for Windows was applied to a 21.76 acre subcatchment in Cambridge, Massachusetts comprised of commercial, institutional, and multifamily land-use types to evaluate the potential reductions of phosphorus attributed to street cleaning. Roof runoff represented between 20 to 50 percent of the total basin runoff. Street surfaces were responsible for about 20 percent of the runoff. Monthly applications of mechanical-brush and vacuum-assisted street cleaners within the subcatchment as defined by SLAMM for areas with long-term on-street parking and monthly parking controls using five average years of precipitation record, resulted in similar total solid reductions of about 23 percent. Monthly street cleaning under the same conditions using productivity function coefficients developed for the regenerative-air street cleaner based on removal efficiency observations in Cambridge, MA resulted in a total solids reduction of about 28 percent. Increasing street cleaning frequency to 3 times weekly increased total solids removal for mechanical-brush, vacuum-assisted, regenerative-air street cleaners to about 25.9, 30.5, and 37.5 percent, respectively.

Monthly applications of mechanical-brush, vacuum-assisted, and regenerative-air street cleaners within the subcatchment resulted total phosphorus reductions of about 12.97, 13.02, and 14.84 percent, respectively. A street cleaning frequency of 3 times weekly for the same three street-cleaner types increased total phosphorus removal to about 14.2, 16.5 and 19.3 percent, respectively.

Introduction

A TMDL (Total Maximun Daily Load) for total phosphorus has been established for the Lower Charles River basin (Massachusetts Deaprtment of Environmental Protection and others, 2007). To meet the total phosphorus criteria in this TMDL, the City of Cambridge is expected to achieve a 65.2 percent reduction in total phosphorus loading contributed to the river from all city sources. A portion of this reduction is expected from the management of non-point source runoff. Structural stormwater control measures (SCMs) are one type of non-point source runoff management, but in urban areas they are limited by the lack of usable space and high installation costs, thus making non-structural SCMs, such as street sweeping (or street cleaning) a more practical alternative. Street cleaning may provide some load reduction, but monitoring these reductions in urban runoff as a result of a street cleaning program is very difficult. Moreover, in a humid area such as Cambridge, Massachusetts, which receives rain about every 3.5 days (NOAA, 2011), the effectiveness of street cleaning to reduce phosphorus loads to the Lower Charles River is further minimized. To better quantify the potential benefits and limitations of high-efficiency (HE) street cleaning, a study has been proposed in cooperation with the Massachusetts Department of Environmental Protection (MassDEP), the U.S. Environmental Protection Agency (USEPA), and the City of Cambridge.

Purpose and Scope

This report describes the physcial characteristics of the material found on street surfaces in predominatly multifamily residential and commercial land-use types within the City of Cambridge, Massachusetts during 10 months of sampling between August 2009 and March 2011. Analytical results of total organic carbon (TOC) and 32 trace elements including phosphorus (P) for selected samples are also presented. The report contains discussions of the physiochemical characteristics of street-dirt samples before and after precipitation events and during periods of dry weather to estimate street-dirt accumulation and wash off due to precipitation. The development of removal efficiency coefficients for a high-efficiency regenerative-air street cleaner based on material collected before and after the use of street cleaner following a monthly street cleaning program is presented. The report also documents the construction and evaluation of the model WinSLAMM to provide phosphorus load reduction estimates resulting from a high-efficiency street-cleaning program within a predominantly commercial land use subcatchment.

Description of the Study Area

The City of Cambridge is a 7.1 square mile (mi^2) urban municipality located in eastern Massachusetts along the northern bank of the Charles River (fig. 1A). The city of Boston borders Cambridge to the south and east. Watertown lies to its southwest and Belmont and Arlington border the west. Somerville borders Cambridge to the north. Topographically, the city generally slopes upward toward the west. Elevation to the northwest at Porter Square and to the southwest at Fresh Pond are about 47 to 40 feet above sea level, respectively (Porter Square observation point, *http://www.wunderground.com/US/MA/Cambridge.html accessed 09/16/2011*, and USGS Fresh Pond gage USGS ID: 422302071083801). Fresh Pond, located in southwest Cambridge (fig1B) is a kettle pond with a 2,000 to 3,000 foot-wide moraine to its south that trends northwest. The surficial geology of the remainder of the city is al is characterized as outwash sands and gravels overlying tills associated with drumlins (Skeehan, 2001).

The 2000 census determined there were about 15,936 persons per square mile in Cambridge, making it the fifth most densely populated city in the United States at that time (2000 census, table C-1). It is estimated that Cambridge has a current population of about 105,162 (2010 census) making it the fifth most populated city in the state. Based on Boston climatic data between 1872 and 2002, the average annual temperature range for the area is about 21 to 81 degrees Fahrenheit. Total annual precipitation is about about 42 inches, which is evenly distributed throughout the year as rainfall and snow (NOAA, 2011).

Figure 1. A. Location map of the City of Cambridge, Massachusetts, and B. its land-use distribution, and municipal street-cleaning districts.

Multifamily residential and commercial land-use types make up more than 40 percent of the total area of the city (table 1, fig. 1B). Three streets representing multifamily and three streets representing commercial land-use types were selected within municipal street-cleaning districts D and E based on sweeping frequency, geographic orientation, traffic volume, street-surface condition, proximity to locations with existing stormwater loading data, and overall safety (table 2, fig. 2). Table 2 shows the basic characteristics of the three predominantly multifamily and three predominantly commercial land-use study street sections including pavement condition index and 24-hour daily traffic count data where available (written commun, City of Cambridge). The lengths of the study sections ranged between 750 and 1304 feet. The average street width was between 25 and 43 feet. In addition, observations of pavement texture and condition and measurements of percent canopy closure are included.

The city employs a monthly street-cleaning program between April and December that uses primarily Elgin Pelican model mechanical brush sweepers, but during April and November a tandem approach using mechanical brush typically followed by a Schwarze S-348 regenerative-air parking lot cleaner is used to pick up the extra street load associated with end-of-winter and leaf-fall seasons. Monthly sweeping is conducted such that even- and odd-numbered sides of the streets in a district are usually cleaned over the course of two days. Street sweeping activities are conducted by contractors and the public works department. Although certain squares, commercial streets, and surrounding areas with limited or no on-street parking are swept weekly or more, most city streets are grouped into well-defined monthly street-cleaning districts (fig. 1). In calendar years 2009 and 2010, about 1,605 and 1,042 tons of material was removed from Cambridge streets, respectively (written commun, Cambridge DPW, 2011).

Table 1. Land use types and percent of total area for Cambridge, Massachusetts (Based on 1999 land-use coverage) Characteristics of study-street sections, Cambridge, Massachusetts

Table 2. Characteristics of study-street sections, Cambridge, Massachusetts

Figure 2. Aerial photo with detail showing the boundary between municipal street-cleaning districts D and E, approximate location of multifamily residential and commercial study street sections, and location of the predominatly commercial land-use subcatchment used in the SLAMM model, Cambridge, Massachusetts.

Previous Studies

The National Urban Runoff Program (NURP) from the late 1970s and early 1980s produced major field sampling efforts and provided the basis of the current understanding of street sweeping effects on urban runoff. Sartor and Boyd (1972) performed the earliest direct experiments to determine street-dirt accumulation and washoff. Pitt (1979) developed sampling techniques to better understand the nature of street-surface materials that are essentially still employed. As part of the NURP projects, the USEPA (1983) determined that urban runoff contains high-P concentrations that contribute to eutrophication. The USEPA (1983) and Pitt (1987) reported that mechanical brush sweepers were found to be only 10 to 30 percent effective at removal of street dirt. Since the NURP era, an increasing number of studies have examined the physical and chemical nature of urban runoff and the potential environmental benefits of street cleaning. Pitt and others (2004) provide tables of selected studies and their respective findings in terms of material accumulation and washoff from street surfaces. Discussion of several selected studies investigating phosphorus runoff and water-quality benefits of street cleaning follows below.

Steuer and others (1997) determined that Marquette, MI lawns were the dominant source (26 percent) of total phosphorus loading which represented 4.5 times the contributing area runoff. In Madison, WI, Washbusch and others (1999) found lawns and streets were the largest sources of total and dissolved phosphorus and total phosphorus loads were proportional to the percentage of runoff at one site (37 percent) and about half at the second site (14 percent). They also observed that 75 percent of the street-dirt mass was greater than 250 micrometers (µm), and less than 5 percent was less than 63 µm.

Breault and others (2005) conducted a study examining the organic and inorganic chemistry and accumulation rates of street dirt in residential areas, and evaluated the relative performance of a mechanical brush and vacuum street cleaners as part of a pilot study in New Bedford, MA. An accumulation rate of about 50 pounds per curb-mile per day (lbs/curb-mi/day) was reported, and coarser fractions such as coarse sand (less than 2 millimeters (mm), greater than 250 µm) appeared to accumulate most rapidly. About 93 percent of the material was found to be greater than very fine sand (>125 µm). Organic and inorganic concentrations of street dirt were similar to other studies, and total recoverable concentrations of phosphorus were about 0.07 percent with the greatest concentrations attributed to the finer fractions. The vacuum street cleaner removal efficiencies were between 62 and 92 percent compared to removal efficiencies between 20 and 31 percent observed for the mechanical brush street cleaner.

Selbig and Bannerman (2007) used a paired-basin approach (Clausen and Spooner, 1993) in Madison, WI to evaluate street-dirt particulate and stormwater loading under control conditions without street cleaning and under street-cleaning conditions using multiple frequencies and three different street-cleaning technologies. Mean and median residential street-dirt yields were reported to be about 614 and 569 lbs/curb-mi, respectively, or about 1.6 tmes the national average reported by Sartor and Boyd (1972). Comparison of paired-basin results indicated that potential load reductions from street cleaning are likely very limited by the extreme variability in stormwater-quality loads. Street cleaners were shown to increase in removal efficiency with increasing street-dirt load. Average street-dirt removal efficiencies of regenerative-air and vacuum-assist cleaners were 25 and 30 percent, respectively. Although a 63-precent increase in ammonia-nitrogen loading was observed in the vacuum-assist cleaner basin at the 10-percent significance level. Weekly operation of mechanical-brush sweepers reduced average street-dirt loads by 5 percent. Increases in street-dirt particles less than 250 µm in diameter was seen after street-cleaner operation. The largest and most evenly distributed yield of street dirt was measured during the spring.

Law and others (2008) conducted sampling and chemical analysis of street dirt from streets in a control and treatment subcatchment in the Cheasapeake Bay area. A conceptual model of pollutant removal rates for weekly and monthly frequencies of mechanical and regenerative/vacuum assist treatments was developed. They collected 10 samples of street dirt before and after a vacuum air cleaner operated over their study streets. A pick-up efficiency of 14 percent was reported, and the lower value was attributed to frequent and intense storm events and the twice-weekly sweeping frequency during their experimental period. An average street-dirt load of 645 pounds per curb-mile (lbs/curb-mi) for their study area and an average street-dirt load of 1,100 lbs/curb-mi was estimated from the control area, which was unswept. Law and others (2008) found that particle-size distribution was similar for before- and after-sweeping street-dirt load samples. They reported about 40 percent of sampled street-dirt load particles were between 250 to 1,000 µm in diameter, and 70 percent of the total street-dirt load consisted of particles larger than 250 µm in diameter. Lead and total phosphorus concentrations were found to be significantly higher in their unswept control basin. The percent contribution of pollutants larger than 250 µm was greater for total phosphorus and total Kjeldahl nitrogen (TKN). This tendancey was attributed to organic matter such as leaf litter in their samples. The resulting estimated range of reductions for total solids (TS), total nitrogen, (TN), and total phosphorus (TP) as a result of street sweeping were 9 to 31, 3 to 8, and 3 to 7 percent respectively.

Fiberglass and asphalt roof types are known to have better runoff quality than slate tile, rubber, or galvanized metal (Davis and others, 2000). Zimmerman and others (2010) collected bulk rainfall samples and runoff samples from a rubberized roof in Ipswich, MA and submitted them for analysis of trace elements and nutrient species as part of an evaluation of various low-impact development (LID) techniques. Average concentrations of copper (Cu), lead (Pb), and zinc (Zn) values from bulk rainfall were about 2.8, 5.9, and 7.9 micrograms per liter (µg/L), respectively. Total phosphorus (P) measured in bulk rainfall was 0.01 milligrams per liter (mg/L). Average concentrations of Cu, Pb, and Zn from the rubberized roof were about 53, 692, and 514 µg/L, respectively, and about 0.10 mg/L was reported for total phosphorus. In addition, roofing and siding materials from buildings has been associated with substantial concentrations of Cd, Cu, Pb, and Zn (Davis and others, 2000).

Smith (2010) conducted an extensive study of storm runoff from locations draining Massachusetts highways of various capacities and traffic densities. In addition to exhaustive stormwater sampling, samples of maintenance sand, maintenance salt (sodium chloride), liquid calcium chloride, berm-soil, and grass clippings were submitted for analysis of trace elements, polyaromatic hydrocarbons, and phthalates. Grasses were found to posses relatively high concentrations of calcium (Ca), potassium (K), and P. Washed leaf samples were also relatively high in these metals (Smith, unpublished). Average concentrations of P, other trace elements, and suspended sediments were reported to be 3 to 11 times greater in winter runoff compared to runoff during warmer months Smith (2010). The large difference between winter and non-winter runoff concentrations was attributed primarily to the application of maintenance sand. Although maintenance sand constituent concentrations were small, the large amount of sand applied suring the winter resulted in large increases of many trace elements, including a 94 percent increase in winter phosphorus concentrations. Low temperatures, increased vehicle component wear, and entrained material in snowbanks are all additional sources of increased winter loading. Smith reported exhaust emissions from gasoline engines at highway speeds represented less than 3 percent of P concentrations in stormwater runoff, background soils accounted for about 37 percent of the median P concentration, and that erosion or presence of soils onto the paved surface could be a large source of P and other trace elements in stormwater runoff.

Urban and suburban traffic patterns have more frequent stops and accelerations. This type of vehicle operation is associated with less efficient combustion by gasoline engines and increased vehicle component and road wear. These conditions in urban and suburban areas may result in greater concentrations of Cu and Zn associated with brake and tire wear (Davis and others, 2000). Average emission rates of Cr, Cu, Ni, and Pb were similar to major particulate-associated polyaromatic hydrocarbon (PAH) emission rates, but P, Fe, and Zn were about 6 to 38 times greater than their respective PAH emission rates (Cadle and others, 2001).

Street-Dirt Collection, Processing, and Chemical Analysis

Street-dirt samples were collected from the surfaces of six street sections detailed in table 2 and shown in figure 2. Three streets were selected in multifamily land-use areas and three streets were located in predominantly commercial land-use areas. Study street sections were selected based on the land-use designation, safety considerations, and street-cleaning frequency. Results should be used to develop average street-dirt characteristics within the two land use types. Samples were collected to characterize the build-up of material, the washoff of material due to precipitation, the removal efficiency of a regenerative-air street cleaner, and the contrations of organic carbon and 32 trace elements including phosphorus.

Street-Dirt Sample Collection

Samples were collected to represent average street-dirt characteristics found in the two land-use types. Sampling methods were the similar to those used by Pitt (1979) and Burton and Pitt, (2002), and the same equipment used in this study was used by Selbig and others (2007). Four nine-gallon, stainless steel wet/dry vacuums with a maximum air flow of 92 cubic feet per minute were used to collect the samples. Each street had a dedicated intake-hose setup that included a six-inch wide aluminum intake nozzle attached to a six-foot long stainless steel wand connected to the vacuum by reinforced black neoprene hose between 15 and 35 feet long (fig. 3). All equipment was kept in the bed of a pickup truck and covered with a hard cap. Aluminum nozzles wore down and their intake width narrowed with use over the rough street surfaces. Nozzle widths were measured before each sampling event and recorded on field sheets. When nozzle widths were less than 5 inches, they were replaced.

Figure 3. Photo of curb-to-curb street-dirt composite sampling equipment and municipal police detail to ensure personnel safety, Cambridge, Massachusetts.

Ten subsamples were collected from ten locations on each street to form a single composite sample for that street. As was done by Selbig and others (2007), 10 individual subsamples were collected and weighed to determine the variability in street-dirt yields, which was then used in an equation developed by Hansen and others (1984) to calculate the number of subsamples needed in a composite sample to accurately represent street-dirt yields. Using an allowable error of 0.50 (or plus or minus 50 percent), the calculated number of samples needed was less than 7. However, if the allowable error was reduced to 0.25, the number of subsamples increased to 49. For this study 10 subsamples were collected for all composites on all streets. Unusual loading conditions such as piles of debris, potholes or construction track out were avoided during sampling to maintain the representativeness of the composite sample. Although 10 markers were painted on the vertical side of the curb on each street section, the sampling locations varied for each sampling event due to the heavy on-street parking which often limited where sampling crews could collect subsamples. The reproducibility of the street-dirt sample collection procedures were evaluated using a Mann-Whitney/rank-sum test. Twelve street-dirt composite sample pairs were used and results showed no significant difference between the pairs of samples ($p = 0.68$). As was shown by Selbig and others (2007), the good precision between sample pairs indicate that sources of variability in street-dirt yields were not introduced by sample-collection techniques.

A single subsample involved vacuuming from curb to curb across the street moving at about 1 foot per second or less with increasing street surface roughness. It was common to see a cleaned path where material was removed following a vacuumed pass (fig 4A). Autumn brought a large amount of leaf material to street surfaces that would often clog the intake nozzle. Therefore under these conditions, leaves along the sample path were manually sampled and placed into pre-weighed and labeled plastic bags. Eleven composite samples were collected during the summer of 2009, and were collected in a manner similar to the procedure described by Selbig and others (2007). Street-dirt material was collected directly into the vacuum stainless steel canisters, its cloth filter was brushed off, shaken into the canister, then all material was brushed out into pre-weighed clear plastic bags. Sample collection was modified for all 2010-2011 vacuumed composite samples, which were collected in pre-weighed 0.1 µm paper filter bags available through the manufacturer. Paper filter bags were chosen to limit field crew exposure to particulate matter, minimize loss of finer fraction to the air, and reduce overall time spent in the field. Composite samples contained in the 0.1 µm paper filter bags were removed from the vacuum canisters, the intake port closed, and material within the bag was allowed to settle to the bottom before it was folded and sealed inside a labeled clear plastic zip-lock bag (fig 5). All curb-to-curb street-dirt sampling events required the use of municipal police details to ensure the safety of field crews (fig.3).

Figure 4. Photo of (A) two cleaned vacuumed paths typical of street-dirt composite sampling, and examples of a rough street-surface and a poor street condition (photo courtesy of Tom Maguire, MassDEP), and (B) a smooth street-surface with good street condition, curb-and-gutter drainage system, and an example of unusual loading avoided during sampling, Cambridge, Massachusetts.

Figure 5. Photo of a street-dirt composite sample contained within a 0.1 micron paper filter bag being extracted from the vacuum, folded, and placed into a labeled clear plastic zip-lock bag, Cambridge, Massachusetts (photo courtesy of Tom Maguire, MassDEP).

Street-Dirt Sample Processing and Chemical Analysis

Street-dirt samples were processed and prepared for shipment to XRAL/SGS for analysis of 32 trace elements and organic carbon at the USGS MA-RI laboratory. Performance evaluation samples (PESs), equipment blank samples, and replicate samples were also prepared and submitted for analysis.

Street-Dirt Sample Processing

Samples were taken back to the USGS MA-RI laboratory, where they were weighed and dried within the paper filter bags for 14 hours at 105°C. Dried samples were weighed again and separated into three grain size fractions: (1) greater than 2 mm, (2) less than 2 mm greater than 125 µm, and (3) less than 125 µm using stainless steel sieves. A 4-mm stainless-steel sieve was used to screen out larger material before sieving; when the sample material was too great for a single set of sieves, multiple sets were used. Sieves were washed using phosphate-free detergent and a tap water rinse, followed by three rinses with deionized water, then dried before each use. Emptied paper filter bags were weighed again and the difference between its tare weight and the weight of the emptied bag was added to the less than 125-micron fraction (defined as fine sand). Resulting masses for each street can be seen in table 1 in Appendix 1. If the relative percent difference between the sum of the three grain-size fraction masses and the initial total dry mass was more than 15 percent, then these data were omitted.

About 10 to 20 grams (g) of representative street-dirt material was subsampled from each of the three separated grain-size fractions, placed into labeled Whirl-pak bags and shipped to XRAL/SGS laboratories in Ontario, Canada for analysis of total organic carbon, total phosphorus, and 31 other trace elements (table 3). In cases where there were large amounts of material or the material too heterogeneous to be subsampled representatively, a riffle splitter was used to yield representative subsamples for analysis. Although leaves and organic debris were not removed from street-dirt subsamples, all visible anthropogenic debris and litter was removed prior to submission for chemical analysis. Resulting total-recoverable concentrations of all curb-to-curb street-dirt composite samples can be seen in table 3 in Appendix 1.

Table 3. Target analytes and analytical techniques for samples submitted to SGS/XRAL Laboratories, Toronto, ON, Canada.

Performance Evaluation Sample Analysis

Six National Institute of Standards and Technology (NIST) standard reference soil 2710 samples and five NIST standard reference soil 2781 samples served as PESs, and were submitted to XRAL/SGS laboratories with street-dirt samples to determine potential contamination bias and overall method performance. Table 4 shows the median analytical results and relative standard deviations of selected constituents for two types of analyses performed on standard reference soil samples: (1) total concentrations, measured in samples fully digested by hydrofluoric acid, and (2) total-recoverable concentrations, measured in samples digested by less agressive acid mixtures. The USEPA has determined that the total-recoverable concentration represents the bioavailability of trace elements in the environment (U.S. Environmental Protection Agency, 1986). The majority of analytical results included in this report were obtained using the total-recoverable digestion.

Table 4. Median values and relative standard deviations (RSD) for selected concentrations of total and total-recoverable trace elements in quality-control samples.

Concentrations certified by the NIST are based on several measurements using two or more techniques from multiple labs utilizing hydrofluoric acid to achieve a complete digestion. About 26 percent of the median total concentrations of trace elements associated with the NIST reference soil 2710 certified values, and about 12 percent of the median total concentrations of trace elements associated with NIST reference soil 2781 certified values that were measured were within their respective certified concentration ranges (table 4). The elements with median concentrations outside the certified concentration ranges were within 16 percent or less of the lower range of certified values of NIST reference soil 2710, and within 15 or less of the lower range of certified values of NIST reference soil 2781. The relative standard deviations for blind sample concentrations of phosphorus and six other major elements of concern (shaded values seen in table 4) were between 4 and 16 percent for the NIST 2710 results and between 2 and 20 percent for the NIST 2781 results, indicating measurements of these elements were fairly precise.

Total-recoverable trace element concentrations obtained using the milder digestion described above resulted in concentrations that were generally lower than the total recoverable concentrations for both NIST standard soils 2710 and 2781 (table 4). However, median total-recoverable concentrations of all constituents in NIST standard 2710 were within about 30 percent or less of the lower range of certified values except for aluminum (Al), barium (Ba), Ca, K, sodium (Na), antimony (Sb) and titanium (Ti), which were between 45 and 94 percent less than the lower range of certified values. All median total-recoverable concentrations of constituents in NIST standard 2710 were within the recovery range except for K, P, Ti, and vanadium (V). Ti, K, and V were 18, 14, and 4 percent greater than the upper limit of the recovery rang, respectively. Phosphorus was about 18 percent less than the lower limit of the recovery range for analyses of NIST standard 2710, indicating a potential negative bias in the total-recoverable concentrations for phosphorus. Median total-recoverable concentrations of all constituents in NIST standard 2781 were within about 9 percent or less than the upper limit of the recovery range except for Al, cadmium (Cd), chromium (Cr), iron (Fe), magnesium (Mg), and manganese (Mn), which were 1 to 28 percent greater than the upper limit of the recovery range. Phosphorus was about 7 percent less than the non-certified value of NIST standard 2781, supporting the potential negative bias in the total-recoverable concentrations for phosphorus seen in the results from NIST standard 2710.

Blank Sample Analysis

Analyses of of total organic carbon, total phosphorus, and 31 other trace elements were also performed on samples of graded unground silica sand. Median results of selected elements were at or below the method detection limit, indicating the silica sand was an appropriate blank material (table 5). The silica sand was then exposed to a precleaned aluminum intake nozzle, neoprene hose, and a preweighed 0.1-micron paper filter bag weighed and dried and then stored for over 48 hours in a similar manner as street-dirt samples collected in the field. The samples were then emptied into stainless steel sieves and shaken for 30 minutes. Analytical results of phosphorus and other selected trace elements in the equipment blank silica sand were also at or below the method detection limit and demonstrate the sampling equipment, filter bags, and processing equipment were not a source of sample contamination.

Table 5. Analytical results of graded unground silica sand used as blank material (determined using half the detection limit for "less than" values) sourced from Ottawa, Illinois.

Replicate Sample Analysis

Replicate samples were also submitted to the laboratory to determine the precision of the laboratory's analytical results. Replicate samples of the PESs (NIST 2710 and 2781 described above) were analyzed using the total and total-recoverable digestions. Median relative percent differences (RPDs) between certified values and resulting total concentrations were about 8 percent using NIST standard reference soil 2710 and about 15 percent using NIST standard reference soils 2781. Phosphorus median total concentration RPDs using NIST 2710 and 2781 were about 6 and 3.4 percent respectively. Median RPDs between NIST 2710 and 2781 certified values and resulting total-recoverable concentrations for all constituents were about 25 and 17 percent respectively, and about 17 and 7 percent respectively for phosphorus in particular. These results are within the 25 percent limit established by the quality assurance project plan (Sorenson, QAPP, written commun, accepted May 2010)

Thirty street-dirt sample split replicates were submitted for analysis and the median RPD of resulting total concentrations for all elements was about 2 percent and about 10 percent for total-recoverable concentrations of all 32 elements. The median RPD for organic carbon analyses was about 8 percent. Evaluation of replicate sample RPDs by grain-size fraction show median RPDs of the greater than 2 mm, less than 2mm to greater than 125 µm, and less than 125 µm fractions of about 23, 15, and 5 percent respectively. Smaller RPDs associated with the smaller grain-size fractions is likely due to the more homogeneous material of the smaller grain-size fractions. Gravel and organic debris such as leaves or sticks were common in the larger grain-size fraction material. Median RPDs of phosphorus for all samples was nearly zero, and ranged from zero to about 111 percent. The larger RPD was associated with the coarser greater than 2 mm fraction. The median RPDs for phosphorus by grain size from coarse to fine were about 26, 11, and 7 percent respectively.

Street-Cleaner Efficiency Sample Collection and Processing

Normal sweeping operations and parking ordinances in Cambridge are designed so that each street is swept over the course of two days each month from April through December. Both sides of Mount Auburn Street were swept in a single day after the city adjusted the sweeping schedule of the southern side from weekly to monthly sweeping for consistency. However, street sweepers were occaisionally seen operating on the study sections. Field crews observed Mount Auburn St being swept outside the normal monthly schedule on two occasions. However, wash-off and removal-efficiency sampling was conducted within relatively short timeframes, which would minimize the chance of unscheduled sweeper operations affecting results. It is unclear if the relatively low street-dirt build-up rate results on Mount Auburn Street discussed in the “Street-Dirt Accumulation” section below are the result of increased street-cleaning frequency.

On those days scheduled for sweeping, the sampling crew would collect 10 subsamples from 10 locations along each street before the street cleaner made a single pass. Each vacuumed strip was 108 in (9 ft) from the curb, which represents the width of the street affected by the street cleaner. Following the collection of the “pre-treatment” samples, a TYMCO Dustless Sweeping Technology-6 (DST-6) regenerative air street cleaner was operated over the street at 5 miles per hour (mph) or less using a single gutter broom (fig.6). Although waterless operation would have provided the most effective removal of all particles, water was applied to the gutter broom, not to the street surface, to minimize pedestrian dust exposure. Immediately following the single street cleaner pass (within about 30 minutes), a second set of 10 composite samples was collected and labeled as “post-treatment” samples. The difference between the pre and post sample masses allowed the determination of the street street cleaner removal efficiency. All samples were collected after the street cleaner made a single pass except for sample events on November 9th and 12th, 2010, when the leaf load on the streets required two passes by the regnerative air street cleaner. During the same time, mechanical brush sweepers made two to four passes before the smaller vacuum-assist machine, operating in tandem with the brush sweeper, made its single pass. No samples were collected on November 10th, 2010 due to rain. Resulting masses of all “pre” and “post” street-dirt composite samples can be seen in table 17. If the relative percent difference between the sum of the three grain-size fraction masses and the initial total dry mass was more than 15 percent, then these data were omitted.

Figure 6. Photo of a TYMCO Dustless Sweeping Technology-6 (DST-6) regenerative-air street cleaner in Cambridge, Massachusetts (photo courtesy of Tom Maguire, MassDEP).

Post-treatment samples contained about 48 grams (g) of material on average and when separated into three grain-size fractions, did not yield sufficient material to subsample for submission to the lab for analysis. Seasonal composite samples were created to provide sufficient material by combining and thoroughly mixing pre- and post-treatment street-street cleaner efficiency samples within the following periods: (1) May to June, (2) July to September, and (3) October to December. Samples were combined into large labeled clear plastic zip-lock bags and sealed. The seasonal composite sample was then shaken and rotated until a homogeneous color and texture was achieved. Representative subsamples of these seasonal composites were obtained using the riffle splitter and were submitted for chemical analysis as described above.). Resulting total-recoverable concentrations of “pre” and “post” seasonal composite samples can be seen in table 18.

Characterization of Street-Dirt

Street-dirt loadings are the result of deposition and removal rates plus "permanent storage" and seasonal components such as leaf-fall and build-up of winter deicing and maintenance (Pitt and others (2004). Seventy-two street-dirt sampling events yielding 172 total mass street-dirt composite samples were collected to better understand the nature of the material on Cambridge multifamily residential and commercial streets. Figure 7 shows the temporal distribution of the curb-to-curb (CTC) and removal efficiency (or single sided, SS) street sampling events as the average street-dirt yield within each land use type observed on each sampling day. Portions of this dataset were used to determine the mass of material, distribution of material on the street surface, accumulation of material, and the washoff of material due to rain events. Subsamples submitted for trace element and organic carbon concentrations from the three streets representing predominantly multifamily residential and three streets representing mostly commercial land use. Although some samples were collected from late July to early September 2009, the majority of samples were collected between May and December, 2010 with two additional sampling events in early March 2011 to represent an end-of-winter load. In addition, ninety-eight sample events resulting in 194 total mass street-dirt composite samples representing pre- and post-street cleaning street-dirt masses used to develop a productivity function, or removal efficiency equation for the high efficiency regenerative air street street cleaner. Removal efficiency samples were collected between May and December 2010 (fig 7).

Figure 7. Daily precipitation and average street-dirt sample yields observed within multifamily/high-denisty multifamily (MF) and commercial (COMM) land-use types during periods of dry weather and bracketed precipitation events (curb-to-curb, CTC), and estimated yields during monthly removal-efficiency experiments (single side, SS) between May 2010 and March 2011. Precipitation data courtesy of the Cambridge Department of Public Works.

Street-Dirt Mass

The average masses of curb-to-curb street-dirt composite samples for multifamily and commercial streets were about 612±8 and 427±3 g, respectively. With the inclusion of the large amounts of street dirt collected in March 2011, the average masses for the two land-use types increase to about 742±10 and 720±13 g, respectively. Comparison of initial sample mass and the mass following 14 hours at 105 degrees C in samples from multifamily and commercial streets indicate the street dirt had an average moisture content of about 21 and 14 percent, respectively. Although sampling protocols required street surfaces to be dry in order to collect composite samples, and areas with ponding were avoided, substantial water content was observed within organic debris along curb areas and during several cold-weather sampling events, water was frozen to the street-dirt material itself.

Pitt (1979) reported that street-dirt yields were a better unit measure of street cleaner performance as it represents the actual mass removed from the street surface. In keeping with this convention, all collected street-dirt mass composites were converted to a composite street-dirt yield in pounds per curb-mile (lbs/curb-mi) using the following expression:

$$P = \frac{\left(\frac{\sum_{i=1}^{n} \left[\left(\frac{M \text{ x } 0.0022}{WN} \right) \mathrm{L_{ft}} \right]}{\sum_{i=1}^{n} \mathrm{L_{mi}}} \right)}{2}$$

where

P	is the mass of the dirt on a street, in pounds per curb-mile;
n	is the total number of streets in each basin;
i	is an index to each street sampled in the study area;
M	is the total mass of sampled street-dirt, in grams;
W	is the width of the vacuum nozzle, in feet;

N is the number of individual strips vacuumed per street;

L_{ft} is the length of each street, in feet;

L_{mi} is the length of each street, in miles;

0.0022 is the unit conversion factor between grams and pounds, and dividing by 2 accounts for two curb-lanes.

Table 6A summarizes street dirt sampled in Cambridge by land-use type and gran-size fraction. Street-dirt yields for multifamily and commercial streets in Cambridge MA are compared to other studies in the United States in table 6B. Multifamily residential average street-dirt yield was about 701 lbs/curb-mi, or about 1.8 times the national average found on residential streets by Sartor and Boyd (1972). Median multifamily street-dirt yield was about 576 lbs/curb-mi. Commercial land-use mean and median street-dirt yields were about 523 lbs/curb-mi, which is about 1.7 times the national average (table 6B). The median commercial yield was about 467 lbs/curb-mi. Mean and median multifamily residential and commercial street yield increased to about 850 and 899, and 612 and 498 lbs/curb-mi, respectively when including the large amounts of material collected in March 2011. Including the end-of-winter yields increased multifamily residential and commercial yields to about 2 to 3 times the reported national average. Evaluation of average street-dirt yields on a seasonal basis required combining results between May and June, July to September, October to December, and March samples to represent spring, summer, fall, and end-of-winter, respectively. The distribution of these seasonal sample groups are seen as boxplots in figures 8A and B. Although there are only two sampling events in March to represent the end-of-winter, figures 8A and B show an annual street-dirt yield cycle that is lowest following the spring cleanup, relatively consistant in summer through early fall, then increases during leaf-fall. Municipal street-cleaning operations end in December, after which street-dirt yields increase during winter. Street-dirt yield observations were greatest during leaf-fall on multifamily streets and at the end-of-winter before street cleaners are re-deployed on commercial streets.

Figure 8. Seasonal and end-of-winter street-dirt yields, in pounds per curb-mile from streets in predominantly A. multifamily residential, and B. commercial land-use types, Cambridge, Massachusetts.

Particle-Size Distribution

Samples were split into three grain-size fractions: (1) greater than 2 mm, (2) less than 2 mm greater than 125 µm, and (3) less than 125 µm, using stainless-steel sieves and sieve shaker. Mean and median RPDs between the sum of the sieved fractions and the total dried mass were 5.6 and 0.87 percent, and ranged between 0.02 and 70 percent. However, there were only five instances where the RPD was greater than 25 percent.

The distribution of material in the three fractions found on the multifamily and commercial streets from coarse to fine was about 32, 54, and 14 and about 19, 67, and 14 percent respectively. The smallest and largest proportions of material were similar for both land-use types. It is likely the greater proportion of > 2 mm material in the multifamily street samples is due to the tree density on those streets compared to commercial streets. In addition, about 87 percent of the composite samples from both land-use types consisted of material coarser than fine sand (or > 125 µm). These results are similar to those of other studies such as that of Washbusch and others (1999), who reported about 75 percent of sampled street-dirt mass in Madison, WI was greater than 250 µm and less than 5 percent was less than 63 µm, Breault and others (2005), where more than 93 percent of the material was greater than 125 µm, and Law and others (2008), where about 70 percent of the material was greater than 250 µm.

Table 6. A. Summary of Cambridge, MA street-dirt yields by land-use type and grain size fraction. B. Comparison of Cambridge, MA street-dirt yields by land-use type to those in other areas of the United States, (modified from Selbig and Bannerman, 2007).

Spatial Distribution of Street Dirt

Distribution of material on street surfaces is highly variable and controlled by many factors including presence of berms or curbing, condition of street-surface texture, prevailing winds, traffic density, on–street parking, and parking controls. Sartor and Boyd (1972), Pitt (1979), and Pitt and Sutherland (1982) observed that on smooth streets with moderate to heavy traffic without on-street parking, about 90 percent of the material was located within one foot of the curb. Pitt (1979) and Pitt and Sutherland (1982) also reported street dirt on rough-textured streets is typically more evenly distributed as more material is retained within cracks and pits on the surface. In addition, they reported on-street parking can act to buffet traffic action and prevailing winds to further limit consolidation of material near the curb. Seasonal effects also determine material distribution. This is demonstrated in areas with relatively cold winters requiring street maintenance during snow events in the form of deicers or sand. Although the Cambridge DPW does not apply maintenance sand to their streets during snow events, maintentance sand tracked into the city from daily traffic and use of sand to improve traction on sidewalks and other pedestrian areas may be available to "wash on" to street surfaces. The city currently applies solid sodium chloride (NaCl) in conjunction with a liquid deicer composed of magnesium, calcium, and agricultural byproduct. In the winter of 2010-11 about 7,500 tons of NaCl and about 2,000 gallons of liquid deicer was applied to Cambridge streets (written commun, Cambridge DPW, 2011).

Selbig and others (2007) collected curb samples from 3-ft out from the curb and crown (or center lane) samples throughout their study. Their streets had minimal on-street parking, and they reported an even distribution of street material at the end of winter such that the crown contained a greater proportion of material than the curb lanes. However, by early summer 75 percent of the street dirt was confined to the curb lanes.

Three sets of street-dirt distribution samples were collected in Cambridge in July and October, 2010, and in March 2011 such that one portion of the composite represented a curb lane and a second composite represented the remaining center lane or crown of the street. July composite samples respresented material within 3 ft of the curb and the remaining street crown. About 57 percent of the total material was found within 3 ft of the curb and about 43 percent of the total material was found in the street crown. In terms of the proportion of material by grain-size, about 67, 55, and 63 percent of the greater than 2 mm, less than 2 mm and greater than 125 µm, and less than 125 µm fractions were within 3 ft of the curb, respectively. Within the crown, the proportions of the same fractions were about 33, 45, and 37 percent, respectively. Samples collected in October were collected 9 ft from the curb. About 95 percent of all material was observed within the 9 ft, and a similar distribution was seen across the three grain-size fractions. From coarse to fine, 97, 91, and 94 percent was seen within 9 ft of the curb respectively. March 2011 represented an end-of winter condition and samples were collected 6 ft from the curb, and about 74 percent of the total material was within this area. From coarse to fine, 81, 72, and 75 percent of the material was seen within 6 ft of the curb, respectively. Although limited, these samples suggest a fairly even distribution of street dirt throughout the year in Cambridge on the smooth to rough-textured streets with heavy on-street parking. The most even distribution was observed within the two coarser fractions (> 2 mm and < 2 mm to > 125 µm), which represents 54 and 67 percent of the total mass on multifamily and commercial streets, respectively.

Street-Dirt Accumulation

Pitt (1979) developed the following expression to represent street-dirt loading:

$$Y = ax - bx^2 + cx$$

where

Y is the street loading at time x;

a,b,c is the second order polynomial coefficients;

ax is the deposition loading;

bx is the amount lost to the air, and

cx is the initial storage loading.

Pitt reported that this function should only be used over the range of observed accumulation periods, and only until a maximum was reached because of the possibility of decreased loading predictions for long accumulation periods. Pitt (1979) discussed the inherent difficulties associated with the collection of street-dirt loading data, and that allowable errors of about 25 percent are common. In addition, if the loading values are not well correlated with accumulation time, linear regression curve fitting may not result in significant street-dirt loading equation coefficients Pitt (1979). Pitt and others (2004) also describe issues using least-squares regression techniques with data containing differing distributions of residual errors over the range of predictor variables, or if the errors are not independent. Further describing how shorter accumulation periods will have greater data density and smaller residual erros compared to the less frequently sampled longer accumulation times, which would have larger residual errors.

Five street-dirt composite samples were used to estimate the accumulation rate (build-up rate or deposition loading) of material on street surfaces by dividing the difference in total yields by the number of days between sampling events. Composite sample data from each street were not always from the same sample dates and were therefore not directly comparable. However, Mount Auburn Street accumulation results were negative while results from all other streets were positive. For this reason, commercial values seen in parenthesis in the following discussions represent commercial street accumulation-rate estimates that exclude Mount Auburn street data due to a potential low bias during accumulation rate sampling discussed in the “Street-cleaner efficiency sample collection and processing" section above. Table 7 shows the average, median, maximum, and minimum build-up rates for each land-use type. Omitting Mt Auburn Street data increased the average commercial build-up rate by about 58 percent. The average multifamily build-up rate was about 30 percent greater than the commercial build-up rate without including Mt Auburn Street data, which is considered the more representative value.

Figure 9 shows boxplots of accumulation rates for each of the three grain-size fractions and total street-dirt yield accumulation within the two land-use types. Overall accumulation patterns are similar between multifamily and commercial grain-size fractions. Median total build-up rates are about 33 and 9 (or 23 without including Mount Auburn St data) lbs/curb-mi/day for multifamily and commercial land-use streets, respectively, and range between about -43 to 84 lbs/curb-mi/day for multifamily streets and about -41 to 308 (-23 to 308) lbs/curb-mi/day for commercial streets. A summary of accumulation rates for the total composite yield and three grain-size fractions for streets within the two land-use types are seen in table 6. Median total multifamily buildup rates are largest within the less than 2 mm to greater than 125 µm fraction at about 19 lbs/curb-mi/day, while the coarser and finest fractions accumulate similarly at about 7 lbs/curb-mi/day. Median commercial buildup rates for the the less than 2 mm to greater than 125 µm fraction are about 9 (15) lbs/curb-mi/day, the less than 125 µm fraction is about 5 (6) lbs/curb-mi/day and the greater than 2 mm fraction was the smallest at about 0.33 (2) lbs/curb-mi/day.

Figure 9. Boxplots of accumulation rates by grain-size fraction and total yield, in pounds per curb-mile per day from streets in predominantly multifamily residential and commercial land-use types, Cambridge, Massachusetts.

Figure 10 shows the average total street-dirt yield and yield by grain-size fraction of material within the two land-use types as a function of days since a rainfall event. The residual loading and overall accumulation pattern of the residential data is similar to the early research of Sartor and Boyd (1972) with a steep increase within the first few days of a washoff or street-cleaning event, then increasing more slowly. Although limited, results indicate that the material on streets within these land-use types in Cambridge can recover to median initial yields between 5 to 17 days after washoff or street-cleaning events. Pitt's work in Bellevue, Washington, an area with rain occurring about every 3 days, showed steady street loadings after about 7 days (Pitt, 1985). Burton and Pitt (2002) indicated that areas with rains evey few days such as Bellevue, WA maintain street-dirt loadings very close to the initial loadings and show little observed increase in street-dirt accumulation with time.

Table 7. Street-dirt accumulation rates and washoff due to precipitation by land-use type. Negative values indicate a net loss of material for build up and a net increase for washoff.

Figure 10. Average total street-dirt yield and yield separated by grain-size fraction, in pounds per curb-mile as a function of time in days from streets in predominantly multifamily residential and commercial land-use types, Cambridge, Massachusetts.

Street-Dirt Washoff

The washoff of material from impervious surfaces is dependent on the available surface particulate load, and the energy of the rain to loosen and transport the material (Pitt and others, 2004). Pitt and others (2004) also summarized that the degradation of the road surface and the deposition of traffic-related materials represent most of the particulate discharges in urban runoff during primarily small and less intense rain evnts. However, exposed soil and dirt surfaces, and normally pervious areas also represent important sources of particulate material during rain events of greater volume and intensity (Pitt and others , 2004). Furthermore, Pitt and others (2004) reported that data from actual streets is highly variable and is affected by street-dirt distributions and armoring (or the sheltering of smaller particles by larger ones). Pitt (1987) showed that washoff model derived by Sartor and Boyd (1972)

$$N = N_0 e^{-krt}$$

where

N	is the street-dirt yield (after the rain, in lbs/curb-mi);
N_0	is the initial street yield (lbs/curb-mi);
k	is the proportionality constant;
r	is the rain intensity (in/hr);
t	is the rain duration;

and modified by Novotny and Chesters (1981) with an availability factor (*A*) to account for rain intensity

$$A = 0.057 + 0.04(r^{1.1})$$

where

r	is the rain intensity (in mm/hr), and
A	is less than 1.0 (equals 1.0 for all rain intensities > 0.71 in/hr [18 mm/hr])

often predicted smaller washoff quantities than what was observed, leading to the development of more responsive washoff models. Pitt's work concluded that suspended solid washoff should be divided between high-intensity rain on streets with large initial loadings, and a second major category representing all other conditions (Pitt, 1987). He provided washoff coefficients for total, suspended, and dissolved solids based on work from several locations (Sartor and Boyd, 1972, Bannerman and others, 1983, Pitt, 1985, Pitt, 1987 and others). The final major consideration is the maximum washoff capacity (W), which determines the carrying capacity of the runoff by

$$W = 0.0636e^{0.237P}$$

where

W is the maximum washoff (grams/square meter (g/m^2), and

P is the average rain intensity (mm/hr).

Thirteen street-dirt composite pairs representing street dirt yields before and after rain events were sampled (fig.7). However, the time between the end of a rain event and post-event sampling varied, and only six sampling events where post-event sampling occurred between about 3 to 23 hours of the end of a precipitation event were used to estimate washoff rates for the two land-use types. The narrow window between sampling events likely eliminated the effects of unscheduled sweeping events, thus commercial washoff values include Mount Auburn Street data. Washoff of street dirt due to precipitation was calculated by taking the percent difference between the sampled mass collected before and after a precipitation event. This was done for six sample pairs and the resulting average total washoff for the six individual streets and both land-use types are seen in table 6. Total storm volumes and rainfall intensities ranged between 0.32 to 1.71 inches (in) and 0.027 to 0.185 in/hr, respectively. Net increases of material following rain events were occaisionally observed and are seen as negative values. One of the six composite sample pairs bounds a rain event during heavy leaf-fall season, which may explain the net increase of material, seen as negative values in table 6. Deposition of organic material from trees, storm “run-on” from other impervious surfaces or saturated pervious surfaces onto the street surface, and construction vehicle track-out are possible explanations for the presence of more material following a “wash-off” event.

Figure 11 shows boxplots of percent washoff for each of the three grain-size fractions and total material with the two land-use types. The median total washoff for multifamily and commercial land-use types were similar at about 35 and 39 percent, respectively. Total washoff on multifamily streets ranges from about -32 to 53 percent, and from about 3 to 63 percent for commercial streets. Negative values indicate a net increase of material following a rainfall event. Washoff by grain-size fraction for all streets was found to generally increase with decreasing grain size. Net increases of material were greatest in coarser material on multifamily streets and in the less then 125 µm fraction on commercial streets. Washoff for material greater than 2 mm on multifamily streets ranged from about -286 to 72 percent and from about -11 to 81 percent for commercial streets. Washoff for material < 2 mm to > 125 µm ranged from about -5 to 63 percent for multifamily streets and from about -2 to 66 percent for commercial streets, and from -6 to 93 percent for multifamily streets and from about -52 to 95 percent for commercial streets for the finest fraction (table 7).

Figure 11. Boxplots of percent washoff due to precipitation, by grain-size fraction, from streets in predominantly multifamily residential and commercial land-use types, Cambridge, Massachusetts.

Figure 12A shows the average percent total washoff and percent washoff of the three grain-size fractions as a function of rain depth for each land-use type. Figure 12B shows the same information as a function of precipitation intensity. Again, washoff generally increases with decreasing grain size, and although observed storm intensities are less than 0.20 in/hr, the largest percent washoff values are seen at intensities less than 0.10 in/hr.

Figure 12. Average total washoff and washoff by grain-size fraction, in percent, as a function of A. total precipitation depth, in inches, and B. precipitation intensity, in inches per hour from streets in predominantly multifamily residential and commercial land-use types, Cambridge, Massachusetts.

Regenerative-Air Street Cleaner Removal Efficiency

The removal efficiency of a TYMCO Dustless Sweeping Technology-6 (DST-6) street cleaner was determined by comparing the difference between sample composites collected before and after the street cleaner made a single pass over a street section. Sample composites were collected within 9 ft of the curb each month over the course of two days for each side of the street between May and December, 2010. The nine-foot sample width represents the area of the street treated by the street cleaner using it's vacuum pickup head and a single gutter broom. Water was applied only to the gutter broom above freezing temperatures to prevent dust buildup in pedestrian areas.

Table 8 shows a summary of the regenerative-air street cleaner street-dirt percent removal efficiencies observed on multifamily and commercial land-use streets. On average, the percent difference between pre and post median total yields on multifamily streets was about 85 percent and about 79 percent on commercial streets. A decrease in removal efficiency with decreasing grain size was observed. Median percent differences observed on multifamily streets were about 92, 83, and 53 percent for the greater than 2 mm, less than 2mm to greater than 125 µm, and less than 125 µm fractions, respectively. Commercial street median percent differences between pre and post yields from coarse to fine, were 92, 79, and 51 percent, respectively. Negative values, or net increases in material were occasionally observed within the less than 125 micrometer (µm) fraction. However, this typically occurred on those streets with rough surfaces, and is thought to be a result of the action of the gutter broom moving material from cracks and holes, in addition to fine-grained material left behind by a wet gutter broom. Figure 13 shows boxplots of street-dirt yields before a single regenerative-air street cleaner pass (pre) and after (post) within both land-use types. Median initial (pre) street-dirt yields within 9 feet of the curb on multifamily and commercial streets were about 735 and 521 lbs/curb-mi, and ranged from 269 to 1,685 to 1,377 lbs/curb-mi, respectively. Median residual (post) yield following a single regenerative-air street cleaner pass between multifamily and commercial land-use types were nearly identical at about 103 lbs/curb-mi, but ranged between 18 and 513 and 46 and 222 lbs/curb-mi, respectively.

Table 8. Average, median, maximum, and minimum removal efficiency, in percent, of a regenerative-air street cleaner on multifamily residential and commercial land-use streets. Negative values indicate an increase in material following a single regenerative-air street-cleaner pass.

Figure 14A shows the residual yield remaining on the surface of the streets following single street cleaner passes as a function of the initial yield. All of the removal efficiency data appears in the area below the 1:1 “no-change” line, below which reductions in street-dirt yield are represented. Although the data in figure 14A does not yield a strong regression, the data pattern appears to be linear at this scale, indicating that efficiency not only increased with increasing initial yields, but that the regenerative-air street cleaner evaluated left a fairly consistant residual median load regardless of the initial street-dirt yield. This also indicates that the regenerative-air street cleaner began to be effective at initial loads between about 51 to 100 lbs/curb-mi.

Evaluation of the removal efficiency data based on season, individual streets, land-use type, street condition, and traffic volume did not present any clear patterns, and resulted in poorer relationships based on too few data points. Closer inspection of all available removal efficiency data showed a non-normal, cloud-like pattern without a strong linear relationship. The Kendall-Thiel robust line, described by Helsel and Hirsch (2002), is a nonparameteric regression technique that is less influenced by outliers and nonnormality of residuals that commonly characterize hydrologic data sets (Granato, 2006). The Kendall-Thiel Robust Line program (KTRLine-version 1.0, Granato, 2006) was used to develop a regression of residual yield (post street cleaning) and initial yield (pre street cleaning) or productivity function for the regenerative-air street cleaner. Figure 14B shows the removal efficiency data plotted in log space and the resulting best-fit line applied to the re-transformed data. The slope is calculated as the median of all possible pairwise slopes and the intercept is calculated so that the line will run through the median of the input data (Granato, 2006). The slope M = 0.066, and intercept B = 69.57 of the KTRLine represent the productivity function coefficients applied in the SLAMM model to simulate the performance of the regenerative-air street cleaner evaluated in 2010.

Figure 13. Boxplots of initial street-dirt yields (PRE) and residual yields (POST) a single pass of a regenerative-air street cleaner, Cambridge, Massachusetts.

Figure 14. A. Removal efficiency plot of a regenerative-air street cleaner making single passes on residential and commercial streets with smooth to rough street-surface conditions, with heavy on-street parking and monthly parking controls within mostly multifamily residential and commercial land-use, Cambridge, Massachusetts. B. Productivity function of the regenerative-air street cleaner using the Kendall-Theil Robust Line (KTRLine version 1.0).

Street-Dirt Chemistry

Median street-dirt composite sample concentrations of organic carbon, phosphorus and thirty-one other trace elements from multifamily and commercial streets were normalized by their respective grain-size fraction masses. Median total-recoverable concentrations, normalized constituent masses, and respective standard deviations of subsamples of all curb-to-curb street dirt sample composites for each grain-size fraction within the two land-use types are seen in table 9A and B. Constituent concentrations were greater on multifamily streets (table 9A) than commercial street (table 9B) concentrations for organic carbon and twelve trace elements. Organic carbon and total phosphorus median concentrations were about 35 and 29 percent greater than commercial street median concentrations.

Total constituent masses from multifamily streets were also somewhat greater compared to those from commercial streets. Masses generally increased with decreasing grain size, except for organic carbon, Ca, K, Mg, P, and strontium (Sr), in results from both land-use types. These constituents had larger concentrations in the > 2 mm fraction than in the < 2 mm to > 125 µm fraction. Organic carbon, Ca, and K, results from the < 2 mm to > 125 µm were also greater than the < 125 µm fraction, although the difference was slightly greater in the multifamily results. Results from samples of unwashed leaves collected from residential streets were found to have high values of organic carbon and these elements, except for Mg. Similar element concentrations were also found in washed leaf samples taken from along Massachsuetts highways (Smith, 2010). About 13.3 and 1.5 percent of the total phosphorus mass is within the finest fraction (< 125 microns) for multifamily and commercial land use types, respectively. However, in terms of total mass of organic carbon and phosphorus, multifamily streets were about 68 and 75 percent greater than the mass collected from commercial land-use streets, respectively.

Figure 15 shows percentiles of phosphorus yields in pounds per curb-mile organized by season for streets in both multifamily and commercial land-use types. Average phosphorus yields on street surfaces as a function of time are shown in figure 16. Phosphorus yields appeared to generally follow the behavior of the average yield of street dirt. Following spring cleaning, phosphorus yields are maintained at realtively low yields by street cleaning and washoff events during warmer months. However, their maximum yields were observed in autumn during leaf-fall season rather than the EOW maximum street-dirt yield (fig. 7). Although significantly reduced following November street-cleaning activities, phosphorus yields continued to be somewhat elevated during the last two months of the street cleaning season (November and December), and during the winter months without street cleaning, phosphorus yields to increase to the second largest yields observed at the EOW in March 2011 (fig. 16).

Table 9. Total and grain-size fraction median constituent total-recoverable concentrations and constituent masses from composite street-dirt samples collected from streets representing (A) multifamily residential, and (B) commercial land-use types. Bold italicized values indicate less than half the detection limit was used to determine concentration and normalized mass.

Figure 15. Boxplots of phosphorus yields, in pounds per curb-mile, by season (where EOW represent end-of-winter), from streets representing predominantly multifamily residential and commercial land-use types Cambridge, Massachusetts.

Figure 16. Daily precipitation and average phosphorus yields observed between May 2010 and March 2011. Precipitation data courtesy of the Cambridge Department of Public Works.

Accumulation Estimates of Organic Carbon and Trace Elements

Concentrations of organic carbon and trace elements were normalized by mass to determine the load of constituents in grams. The resulting mass was then used with the Pitt (1979) equation described in the "Street-Dirt Mass" section above to determine the yield of each constituent in pounds per curb-mile. The difference between resulting yields was divided by the total number of days between sampling events to further obtain estimates of constituent accumulation rates in lbs/curb-mi/day. Average, median, maximum, and minimum accumulation rates in terms of land-use type and grain-size fraction are seen in table 10. Negative values indicate a net loss of material on street surfaces, and brush sweeper operation outside the scheduled monthly operations discussed above may have influenced Mount Auburn Street data. Commercial values not including Mount Auburn Street data are seen in parenthesis in this section. Multifamily organic carbon and trace element median accumulation rates are greater than those observed on commercial land-use streets for 24 of the 33 constituents tested within the greater than 2 mm and less than 125 µm fractions, and for 14 of the 33 constituents tested within the less than 2 mm to greater than 125 µm fraction. Coarse to fine grain-size fraction multifamily median accumulation rates were greater than commercial median accumulation rates without Mount Auburn St data for 31, 24, and 16 of the 33 constituents tested, respectively.

Table 10. Buildup of constituent masses, in pounds per curb-mile per day, by grain-size fraction and land-use type from samples composites collected before and after precipitation events. Negative values indicate a net loss of material.

Yields were generally smallest within the > 2mm fraction, except for organic carbon. However, the largest yields appear to vary between the < 2 mm to >125 micron and the < 125 micron fractions (table 10). Yields from multifamily land-use streets were generally greater than those observed on commercial land-use streets. In particular, the median total yields of Cr, Cu, P and Pb from multifamily streets were about 1.87, 1.38, 5, and 12.7 times greater than commercial median total yields, respectively. However, commercial median total yields of Cd, Ni, and Zn were greater than multifamily yields by about 2, 1.9, and 1.5 times respectively.

The organic carbon median accumulation rate for all multifamily data was 1.43 lbs/curb-mi/day and ranged between about -11 to 17 lbs/curb-mi/day. The median organic carbon accumulation rate and range for all commercial data was 0.057 (0.067), and ranged between about -12 to 4 lbs/curb-mi/day whether Mount Auburn St data was included or not. Organic carbon yields were greatest within the < 2 mm to >125 µm fraction, followed by the the > 2 mm fraction for both land-use types reflecting the dominant influence of larger organic debris within the coarser fractions. The total phosphorus median accumulation rate for all multifamily data was 0.0004 lbs/curb-mi/day and ranged between about -0.003 to 0.077 lbs/curb-mi/day.The largest yields of P appears within the < 2 mm to >125 micron fraction, but also in the < 125 µm fraction. From coarse to fine, multifamily median accumulation rates of P are about 0.001, 0.004, and 0.010 lbs/curb-mi/day, respectively. The total phosphorus median accumulation rate for all commercial data was 0.00005 lbs/curb-mi/day and ranged between about -0.003 to 0.024 lbs/curb-mi/day. Median commercial build-up rates from coarse to fine are about 0.00005, 0.004, and 0.0001 lbs/curb-mi/day, respectively. The > 2 mm fraction increased from 0.00005 to 0.0001 lbs/curb-mi/day upon omitting data with potnetial low bias. All other estimates remained the same.

Washoff Estimates of Organic Carbon and Trace Elements

Percent washoff of constituents was determined by multiplying the trace element concentrations by their respective grain-size fraction masses for six composite sample pairs. Table 11 shows the average, median, maximum, and minimum percent washoff of organic carbon and 32 trace elements for all data and by each grain-size fraction within the multifamily and commercial land-use types. Similar to the accumulations rates seen in table 10, median organic carbon and trace element accumulation rates on multifamily streets are greater than those observed on commercial land-use streets for 24 of the 33 constituents tested within the greater than 2 mm and less than 125 µm fractions, and for 14 of the 33 constituents tested within the less than 2 mm to greater than 125 µm fraction. Negative washoff or net increase of constituent masses was observed for several storm events in all grain-size fractions, but was most common within the greater than 2 mm and less than 125 micron fractions. These events may be likely associated with organic debris and "washon" from other source areas onto the streets. Median percent washoff was greater on multifamily streets compared to commercial streets for 24 of the 33 constituents for the greater than 2 mm and less than 125 micron fractions, and greater than commercial streets for 14 constituents for the less than 2 mm to greater than 125 micron fraction. Multifamily median total washoff of phosphorus is about 58 percent and ranged between -1120 to 93 percent. Multifamily median washoff of P is about 39 percent for the two coarser fractions greater than 125 µm, and about 76 percent for material less than 125 µm. Median commercial total washoff of phosphorus was about 48 percent and ranged between about -214 to 99 percent. Median commercial washoff of P from coarse to fine are about 34, 51, and 77 percent, respectively.

Table 11. Washoff of constituent masses from samples collected before and after precipitation events in terms of grain-size fraction and land-use type. Negative values indicate a net increase of material.

Estimates of High-Efficiency Street Cleaner Removal of Organic Carbon and Trace Elements

Constituent mass reductions as a result of street cleaning were estimated by using median analytical results from the spring, summer, and fall seasonal street-dirt composites, described in the sample collection and processing section above, normalized by their respective median seasonal grain-size fraction mass of material, to obtain an estimate of the mass of each constituent removed following a single pass of the regenerative-air street cleaner over the study street sections. Tables 12A and B show the median percent reduction in terms of total and grain-size fractions for organic carbon and 32 trace elements based on total-recoverable concentrations of seasonal subsamples of pre- and post-street cleaner operation composite samples. Percent reductions generally decrease with decreasing grain size, and reductions were slightly less during the spring and summer months, which reflects the relatively lower street-dirt yields observed compared to the larger end-of-winter cleanup and autumn leaf-fall loading. Constituent reductions are greater on multifamily streets for nearly all constituents greater than 125 µm (table 12A), but are less than commercial reductions (table 12B) for 20 of the 33 constituents within the greater than 2 mm, and all other constituents less than 125 µm except for silver (Ag). Negative values indicate an increase in the mass of a constituent following street cleaner use, and are seen almost entirely in the less than 125 micron results from multifamily residential streets in the fall composite results (table 12A). Net increases within the less than 125 micron fraction are seen for tin (Sn), Pb, Ni, Cu, chromium (Cr) and arsenic (As). The range of percent reductions on multifamily streets for all constituents are between 50 and 98 percent during the spring, -37 and 100 percent for the summer samples, and -1,050 and 99 percent for the fall. Commercial street percent reductions showed one negative value within the greater than 2 mm spring sample for cobalt (Co). Spring, summer, and fall percent reductions of all constituents ranged between -8 to 98, 14 to 99, and 60 to 99 percent, respectively. In terms of phosphorus percent reductions, multifamily street results show between 94 and 100 percent was removed within the greater then 2 mm fraction, between 86 and 99 percent within the less than 2 mm to greater than 125 µm fraction, and between 66 and 96 percent within the less than 125 µm. Percent reduction of phosphorus on commercial streets from coarse to fine fractions show between 83 and 96, 97 and 98, and 79 and 97 percent, respectively.

Table 12. Total and grain-size fraction median constituent percent reductions from seasonal composite street-dirt samples collected before and after a single pass of a regenerative-air street cleaner on streets representing (A) multifamily residential and (B) commercial land-use types. Bold italicized values indicate less than half the detection limit was used to determine concentration and normalized mass. Negative values indicate a potential net increase of a constituent.

Source Loading and Management Model

The Source Loading and Management Model for Windows (WinSLAMM, referred to as SLAMM) version 9.4.0 (Pitt and Voorhees, 2002) is a program capable of continuously simulating stormwater runoff, loading of suspended sediments and other constituents, and the effects of stormwater-control measures under various precipitation conditions. SLAMM was chosen because it has been successfully used to evaluate the performance of many types of stormwater control measures, including street cleaning, in locations across the United States and Canada. SLAMM was developed in the late seventies and since that time has been dramatically modified by incorporating substantial amounts of new data from other studies. Initial simulations used these data included with the model to match existing runoff and loading data.

Potential reductions in phosphorus associated with high-efficiency street cleaning practices were simulated for a predominatly commercial land-use subcatchment in Cambridge, Massachusetts that ultimately drains to the lower Charles River (fig. 2). Street-dirt data collected as part of this study and geographic information provided by the city of Cambridge and other sources were used to develop the model specifically for the study area.

Functional Description of SLAMM

SLAMM uses a mass balance approach to track particulate and dissolved constituents associated with up to six different land-use types and their source areas, taking into account a variety of rainfall conditions and source-area control measures. Runoff, constituent mass discharge and effects of selected control practices are the primary model output. SLAMM can also output other types of information such as the relative contribution of source areas within each land-use type and generation of National Resource Conservation Service (NRCS) curve numbers that represent the modeled land-use and control measures.

The model emphasizes the concept of small storm hydrology and particulate washoff to better simulate stormwater quality. This emphasis follows a major finding of the NURP-era work indicating common small rainfall events represent the largest proportion of the annual urban runoff discharge quantities (USEPA, 1983 and Pitt, 1987). The model also takes into account the findings of Maestre and others (2005), where log-transformed constituent concentration data in stormwater generally have a lognormal distribution between the 5th and 95th percentiles. A Monte Carlo option in the model provides the means to determine variations in the constituent concentrations in source area runoff and yield the median values used for mass balance calculations. This feature can be deactivated and discrete concentration can be used to allow evaluations of extreme concentrations. SLAMM can also be used with other models such as the Hydrologic Simulation Program Fortran (HSPF) and the StormWater Management Model (SWMM) to improve simulations of stormwater and water-quality controls.

Simulations in SLAMM require six input parameter files, which are based on actual data collected from many different studies across the United States and Canada since the late seventies and continue to be modified as new data become available. It is possible to simulate different stormwater control practices using precipitation data from a single year or several decades. SLAMM simulations can yield accurate predictions of stormwater quality for a drainage area with only limited ancillary information. However, version 9.4 of SLAMM does have several limitations, including the inability to simulate baseflow or snowmelt conditions, evaluate in-stream processes that affect constituent mass, or model erosion from pervious areas and construction sites. The model also uses simplified drainage system routing compared to the detailed water routing through certain stormwater control measures such as grass swales or detention ponds, and it cannot currently simulate rural areas effectively or conduct design storm analyses.

Local outfall stormwater quantity and quality data from several watersheds with relatively homogeneous land uses should be collected and used to calibrate SLAMM. Ideally, data from one set of watersheds or subcatchments should be used to calibrate the model, and data from the remaining subcatchments used to verify model performance. Alternatively, a subset of data from a single location can be used for model calibration and any remaining data from the same location used for verification. These approaches assume availability of good quality data. However, available data for this study was limited in number and quality.

Description of Commercial Land-Use Subcatchment

The subcatchment representing mostly commercial land use was selected for this study due to the existing level, flow, and loading data at its outfall that was available from previous USGS studies (Breault and others, 2002 and Zariello and others, 2002) and is seen in figure 17. In addition, street-dirt data was collected from streets in and around this subcatchment (fig 2). Massachusetts Avenue and Mount Auburn Street are the two major routes that cross the basin, and 24-hour traffic traffic counts from 2002 were 11.670 and 9,860, respectively (City of Cambridge, written commun, 2009). Areas of Mass Ave are sweept daily and weekly. The southern side of Mount Auburn Street has a dedicated bicycle lane that is typically swept weekly, while the northern side is swept monthly following the schedule for Street-cleaning district E (fig. 2). The street-cleaning schedule for both sides of Mount Auburn St was changed to monthly between May and December, 2010.

The outfall monitoring location for the commercial land-use station (USGS ID: 01104677) was a 3-ft diameter concrete storm drain located on Mount Auburn Street near Banks Street representing about 76.4 percent commercial and about 23.6 percent multifamily land use. During 1999 and 2000, 14 dry- and 10 wet-weather sample events were collected from the 14.6 acre (0.023 mi^2) subbasin (Breault and others, 2002). However, additional areas were thought to contribute additional runoff to the monitoring location during some storm events and the resulting total area increased to 21.76 acres (Zariello and Barlow, 2002). Zariello and Barlow (2002) also determined the commercial subbasin contained about 86 percent effective impervious area (EIA).

Figure 17. Predominantly commercial land-use subcatchment in Cambridge, Massachusetts and USGS flow and water-quality monitoring station (USGS ID: 01104677), over a 0.5-meter color orthophoto obtained from MassGIS.

Several limitations need to be considered when using these data: (1) level and velocity records from the site were incomplete, and estimation techniques were needed to fill these data gaps (Zariello and Barlow, 2002); (2) Zariello and Barlow (2002) used the limited level and discharge data from the commercial subbasins to develop rainfall-runoff relations from low-intensity storms with rainfall-runoff coefficients less than 1.0; (3) water-quality samples were collected in a flow proportional manner from a fixed location pointing downstream on the bottom of the drainage pipe. Under these conditions sand-sized particles (greater than 63 µm) generally form a vertical gradient (Bent and others, 2000), and sampling in this manner potentially resulted in a large positive bias in total suspended sediment concentrations following the work described by Smith (2002); and (4) other constituents that can be associated with high coarse-grained sediment concentrations such as phosphorus may also be affected by the vertical gradient formed within the water column at the time of sampling.

Input Data used for Modeling of Land-Use Subcatchments

Detailed information is required to characterize the drainage area to be modeled. Drainage boundaries, land-use types and their respective sources areas must be determined (table 13). Drainage systems and other control practices must also be identified. SLAMM parameter files (table 14) must be input and modified as needed following their general order of calibration. Required information and the data contained in the parameter files used for SLAMM simulations of the commercial subcatchment are discussed in the following sections.

Delineation of Land-Use Types and Source-Areas

Characterization of land-use types and their respective source areas within the model subcatchments were delineated from impervious surface geographic information system (GIS) coverages generated by the City of Cambridge or their contractors (table 13). The 2005 land-use coverage available through MassGIS was used (fig. 18, MassGIS, *http://www.mass.gov/mgis/lu.htm*, accessed February 12, 2011). Municipal coverages provided greater source-area resolution than the 1-meter impervious surface raster layers based on 2005 0.5-meter color ortho mosaic index provided by MassGIS (MassGIS, *http://www.mass.gov/mgis/imp.htm*, accessed February 12, 2011). However, their 0.5-m orthophoto provided qualitative visual confirmation (MassGIS, *http://www.mass.gov/mgis/colororthos2005.htm*, accessed February 12, 2011). Using the municipal GIS layers, all constructed surfaces and areas of man-made compacted soils were considered impervious. All surface waters, wetlands, natural and man-made vegetated areas were considered pervious. Roof, driveway, and other impervious surface drainage was further evaluated in the field to determine connectivity. If runoff drained to less than 20 feet of pervious area, the drainage was considered directly connected.

Land-use types and their respective source areas as input to SLAMM are seen in table 13. About 36 percent of the commercial subcatchment is considered multifamily or high-density residential land use, about 17 percent institutional, and about 47 percent commercial land use. The model treats institutional and commercial areas the same, so the effective commercial land use is about 67 percent.

Table 13. Source-area designations and respective areas as input to SLAMM model within the commercial subcatchment, Cambridge, Massachusetts.

Figure 18. Predominantly commercial land-use subcatchment in Cambridge, Massachusetts and USGS flow and water-quality monitoring station (USGS ID: 01104677), over the 2005 land-use coverage obtain from MassGIS.

Soils

Soils in the subcatchment area (Middlesex County) are typically considered disturbed urban galcio-fluvial outwash (U.S. Department of Agriculture, 1995). Despite highly permeable classifications of parent soils, pervious areas were represented as “silty” rather than “sandy” within the model to account for the effects of compression and buildup of fugitive dust that substantially reduce native soil permeability (Pitt and others, 2008).

Control Practices

The city possesses a well-defined curb-and-gutter drainage system equipped with steep granite curbstone that is essentially normal to the road surface (fig 4). Catchbasins are incorporated into the drainage system and are cleaned about twice a year. As mentioned above, the city utilizes a monthly street-cleaning program with parking controls between April and December that employs mechanical brush sweepers. A tandem street cleaning approach (mechanical brush followed by vacuum assist) is applied during the months of April and November to target the much larger street-dirt loadings associated with end-of-winter and leaf fall seasons. In addition, many commercial areas and city squares are swept weekly or daily.

Base model simulations used to compare with flow and water-quality data collected in 1999-2000 were run by specifiying monthly mechanical street cleaning in the model. Productivity function coefficients provided with SLAMM for mechanical street cleaners (M = 0.85 and B = 310) were used. Model performance was also evaluated by comparing simulated street-dirt yield to street-dirt observations from 2009-2011. These simulations specified monthly vacuum-assist street cleaning using productivity function coefficients developed from the regenerative-air street cleaner observations in Cambridge. Catcbasins were not included in the model.

Street-Dirt Accumulation

The observations of material buildup on street surfaces in Cambridge collected in 2010-2011 were used to populate SLAMM accumulation coefficients. The multifamily average accumulation rate (m) was set to 30 lbs/curb-mi/day, the intercept load (b) was set to 225 lbs/curb-mi, and the maximum load (C) was set to 3800 lbs/curb-mi. The end-of-winter (EOW) load for residential land-use streets was set at 2600 lbs/curb-mi. Commercial and institutional land-use accumulation coefficients m, b, C and EOW were set to 20, 225, 1400, and 4800, respectively.

Rainfall

Initial model runs utilized 62 years of rainfall data from Boston's Logan Airport (1948-2010 COOP ID: 190770) available through the National Climatic Data Center (NCDC *http://cdo.ncdc.noaa.gov/dlyp/DLYP*, accessed February 12, 2011). Storms less than 0.1 inch were omitted from all *.RAN files, (i.e. only runoff producing stroms were considered). A special *.RAN file was created from the long-term Logan Airport data to determine the average storm duration of storm depths between 0.10 to 5.00 inches. SLAMM runs using the special *.RAN file yielded the relative contribution of runoff from each source area over the range of storm volumes and provided the basis for any modifications to runoff coefficient *.RSV parameter files. Logan Airport rainfall data was also used to evaluate simulated outfall runoff and loading compared to water-quality data collected in 1999-2000. Additional *.RAN files developed using precipitation records from the Cambridge Department of Public Works (DPW) Hampshire St gage supplemented by the USGS Fresh Pond gage (USGS ID: 422302071083801) during winter months were used to evaluate model performance in terms of street-dirt loading observations in 2009-2011.

The base model that provided acceptable estimates of runoff and street-dirt loading was then run using five years of precipitation data from the Boston's Logan Airport gage that represented the average climatic conditions. The five average years were selected by comparison of annual discharges from the USGS Aberjona River at Winchester, MA gage (USGS gage ID: 01102500, located about 7 miles north of Cambridge) with the site's 70-year mean annual flow of 31.1 cubic feet per second (cfs) (Bent and others, 2009). Years with annual average discharge within 4.5 percent of the Aberjona River's 70-year mean annual flow were 1948, 1953, 1961, 1986, and 1991. Model runs using a *.RAN file based on these data allowed SLAMM to generate average estimates of street cleaner performance in terms of sediment and phosphorus reductions.

Runoff

Runoff coefficient (R_v) parameter files (*.RSV) contain ratios of runoff quantity to precipitation quantity for all modeled surface types for rain depths between 0.01 to 5 in. The WI_SL06 Dec06.RSV file provided with the model was initially used, and examination of the relative contribution of source areas generated by the model run using the special *.RAN file, runoff coefficients were modified in a stepwise manner to improve agreement between simulated results and runoff data from 1999-2000. Runoff coefficient increases between 0.05 and 0.10 were found to be sufficient to better match simulated and observed outfall flows.

Particulate Solids Concentration

Suspended solids concentrations (SSCs) associated with source areas from each land use over a range of rain depths is contained in the particulate solids concentrations (*.PSC) file. Build-up and washoff functions directly predict roads and highway surface SSCs, and are not included in the *.PSC file (Pitt and Vorhees, 2000). The WI_AVG01.PSC file provided with the model is based on data from Madison, WI that represents the most recent data and best average particulate solids information. No new outfall SSC data was collected in Cambridge to support modifications to this *.PSC file, and therefore the WI_AVG01.PSC file was used for calibration and subsequent SLAMM simulations.

Two additional parameter files are used to describe the transport of particulates in SLAMM. The first file is the particulate residue reduction file (*.PRR), and was designed to account for the deposition of particulates in the storm drainage system before the outfall or outfall controls (Pitt, 2008, Pitt and Voorhees, 2000). However, particulate deposition in the storm drainage system is now directly calculated, making the *.PRR file obsolete (Pitt, 2008). SLAMM still requires a *.PRR file to be specified, and the file WI_DLV01.PRR, set to zero, was used as a placeholder in the model. The second additional file is street-dirt delivery file (*.STD). These files account for the fraction reduction in street dirt yield during washoff events between 0.04 to 3.2 in. Fraction washoff is applied to street surfaces with textures ranging from smooth to very rough within each land-use type. The files WI_Res and Other Urban Dec06.STD, WI_Com Inst Indust Dec06.STD, and Freeway Dec06.STD were used in the model. These files typically show 100 percent washoff for all surface types for storm depths greater than 0.60 in.

Pollutant Concentrations

The *.PPD file contains particulate and dissolved pollutant concentrations associated with each source area for each land-use type specified in the model. This file only needs to be specified for pollutants other than particulate solids. Coefficient of variation (COV) values are also included for each constituent for Monte Carlo simulations (Pitt, 2008, Pitt and Voorhees, 2000). The WI_GEO01.PPD was applied to model of the Cambridge commercial subcatchment. The critical particle size file (*.CPZ) is primarily designed to assist evaluations of wet detention ponds and other structure SCMs. SLAMM comes with several *.CPZ files that describe particle size ranges in areas associated with low to high particulate residue concentrations as well as files that contain the average of the NURP-era studies and a regionally-specific *.CPZ file. The critical particle size parameter file was not necessary for SLAMM simulations of street cleaning in this study, and no *.CPZ file was specified.

Table 14. Parameter files and other model data required to develop SLAMM for the commercial subcatchment Cambridge, Massachusetts.

Model Performance

The general order of calibration begins with runoff, followed by particulate solids, and then constituents. Initial SLAMM simulations were evaluated using the special *.RAN file to guide modifications to the *.RSV file to match existing runoff data from 2000. Only after acceptable agreement between simulated and observed runoff was achieved, were evaluations of simulated and observed street-dirt yields from 2009-2011 possible.

Relative Contributions of Source Areas

The special *.RAN file based on 62 years of precipitation record at Boston Logan Airport (COOP ID: 190770, table 14) yielded relative runoff contribution data seen graphically as cumulative curves for each of the three land-use types in the subcatchment in figure 19A-C. Residential land-use (fig 19A) appears to be dominated by roof runoff, contributing between about 37 to 54 percent of the multifamily and high-density residential area's total runoff. Streets represent the next largest fraction of runoff (about 18 percent) followed by driveways (about 13 percent), sidewalks and walkways (about 11 percent), and paved parking (about 7 percent).

The relative contribution of institutional land-use runoff (fig 19B) shows an even greater preportion of runoff attributed to rooftops between about 30 to 60 percent (including disconnected roof areas). Driveways and paved parking areas make up the next largest proportion of runoff contributing between about 18 to 30 percent. Street surfaces contributed a fairly consistent proportion of about 16 percent, followed by about 10 percent contributed by sidewalks and walkways. Both residential and institutional land uses in this subcatchment show increasing contribution from landscaped areas with storm depths greater than about 1 inch where saturation and “run-on” from normally “pervious” areas into the drainage system likely occurs. These pervious areas appear to contribute about 10 to 12 percent of the total runoff during rain events greater than about 4 inches.

The commercial land use percent contribution is seen in fig 19C. Rooftops contributed between about 23 to 50 percent, street surfaces between about 20 to 28 percent driveways and paved parking about 18 to 36 percent, and sidewalks about 10 to 17 percent. This land use contained little landscaped area and such pervious surfaces do not appear to contribute any runoff.

Available runoff data was collected for storm depths between 0.25 and 2.0 in, and model runoff estimates outside of this range are associated with greater uncertainty. Modifications to runoff coefficients were therefore based only on simulation results between these precipitation depths. Modifications were made in a stepwise manner beginning with runoff coefficients from source areas with the greatest relative contribution and ending with those areas contributing the least.

Figure 19. Cumulative relative percent contributions of major source areas within the (A) multifamily and high-density residential, (B) institutional, and (C) commercial land-use types contained in the commercial subcatchment, Cambridge, Massachusetts.

Model Output Compared to 1999-2000 Runoff and Water-Quality Data

The thirteen runoff observations from 2000 were first evaluated to determine the quality of the data for comparisons with simulated runoff. Figure 20A and B show plots of rainfall depth versus runoff depth and runoff coefficient versus ranfall depth, respectively. Although there is some scatter, the general trend appears reasonable for mostly directly connected areas associated with the subcatchment.

Initial SLAMM simulations were run using the parameter files provided with SLAMM and ten years of Boston Logan Airport data, and resulted in a mean runoff depth percent error between simulated and observed runoff of about 33 percent and the sum of the percent differences was about 28 percent. Following examination of the relative contribution plots seen in figure 19, the selected *.RSV file was modified in a stepwise manner until an acceptable agreement was obtained between simulated runoff and the thirteen observations from 1999-2000.

Figure 21 shows the observed versus the simulated runoff of the commercial subcatchment. Despite the scatter about the 1:1 line, the mean runoff depth percent error improved to about -11 percent and the sum of the percent differences was -2.31 percent. Figure 22 shows how the simulated time series of runoff compares to the observed runoff data.

Figure 20. Plots of (A) rainfall depth versus runoff depth, and (B) runoff coefficient versus rainfall depth from the commercial subcatchment outfall observations in 2000, Cambridge, Massachusetts (USGS ID: 01104677)

Figure 21. Simulated versus observed runoff depth from the commercial subcatchment, 2000, Cambridge, Massachusetts (USGS ID: 01104677).

Figure 22. Time series of simulated outfall discharge from the commercial land-use subcatchment compared to observed discharge, March to December 2000, Cambridge, Massachusetts (USGS ID: 01104677).

Initial simulations of particulate solid concentrations and loads resulted in mean percent error between simulated and observed TSS of about -43 and -140 percent, respectively. Simulations using the modified *.RSV file resulted in a minor improvement in particulate solid concentrations to about -40 percent and further decrease in particulate solids loads to about -163 percent. Due to the potential high bias in the observed TSS values, and the high number and quality of the particulate solids concentration data contained in the WI_AVG01.PSC (Bannerman, oral commun, 2011), there was little support for modifications to the *.PSC file to further improve the particule solid simulation results.

In terms of particulate phosphorus, the initial model resulted in mean percent error between simulated and observed particulate phosphorus loads of about 54 percent. Simulations using the modified *.RSV file resulted in an improved mean percent error between simulated and observed particulate phosphorus loads of about 16 percent.

Model Output Compared to 2009-2011 Street-Dirt Yield Data

The base model equipped with the modified *.RSV file was then run using three years of precipitation data from the Cambridge DPW and the USGS to match street-dirt sampling between August 2009 to March 2011. Resulting simulated street-dirt output data was then compared to street-dirt observations as a form of verification of model performance. Productivity function coefficients $m = 0.07$ and $b = 70$ were input and the model was run. Figure 23 shows a plot of simulated versus observed street-dirt yields for streets characterized as multifamily/high-density residential and commercial/institutional land uses with the 2010 data only. Mean percent error between simulated and observed street-dirt yields for the multifamily/high-density residential land use streets is about 22 percent, and for the commercial/institutional land use streets is about -13 percent. The sum of the percent differences between simulated and observed was about -7 and 11 percent for multifamily and commercial/institutional streets, respectively. Removal of data collected in November during the highest periods of leaf-fall from both land-use types improved the mean percent error for multifamily and commercial/institutional streets to about 6.4 and 6.5 percent, respectively. However, multifamily sum of the percent differences between simulated and observed street-dirt loads increased to about -19 while commercial/institutional streets decreased to less than -2 percent. Figure 24 A and B show time series of multifamily residential and commercial/institutional land use street-dirt yield simulations compared with their respective field observations. Gaps in simulated data correspond to non-storm and non street-cleaning sampling events that were not simulated by the model. These plots show reasonable agreement between simulated and observed points. However, the model undersimulates the autumn period of leaf-fall, which is associated with some of largest street-dirt loadings. Elevated street-dirt loadings seen during summer months are perhaps associated with construction track out, deposition of organic material, or the highly variable nature of the street material or some combination of these.

Figure 23. Simulated versus observed street-dirt yields, Cambridge, Massachusetts.

Figure 24. Simulated and observed street-dirt yields, April to December 2010 for A. multifamily/high-density and B. commercial/institutional land-use types within the commercial land-use subcatchment Cambridge, Massachusetts.

Model Simulations

The SLAMM model was used to estimate potential reductions of total solids and total phosphorus resulting from various street-cleaning technologies and frequencies. Mechanical brush and vacuum assisted street cleaners were simulated using productivity function coefficients supplied with SLAMM. Simulations using a second “vacuum-assisted” street cleaner using productivity function coefficients developed from the removal efficiency experiments described above represented the regenerative-air street cleaner.

Street Cleaning Program Performance Under Average Climatic Conditions

The five average years *.RAN file was used to simulate mechanical brush, vacuum-assist, and regenerative-air street cleaners at the following frequencies: monthly, bi-monthly, weekly, and 3 days per week. Mechanical and vacuum-assist productivity function coefficients were generated by SLAMM based on long-term, on-street parking conditions with parking controls specified. Mechanical brush street cleaner productivity function coefficients were m = 0.73 and b = 310. Vacuum assist coefficients were m = 0.70 and b = 41. Coefficients for the regenerative-air street cleaner evaluated on Cambridge streets were the same as those used to match simulated street dirt to observed street dirt: m = 0.07 and b = 70.

Table 15 summarizes the estimated percent reduction of total particulate solids and total particulate phosphorus and the flow-weighted average of these two constituents for each street cleaner type and operational frequency. Simulations of monthly mechanical brush street cleaning resulted in reductions of total solids and total phosphorus of about 2.72 and 1.41 percent, respectively. Total particulate solids and particulate phosphorus reductions were about 4.20 and 2.05 percent, respectively. Estimated reductions resulting under mechanical-brush street cleaning 3-days per week yielded total solids and total phosphorus reduction estimates of about 6.01 and 3.05 percent, and total particulate solid and particulate phosphorus reduction estimates of about 9.47 and 4.48 percent, respectively.

Simulated reductions of total solids and total phosphorus and total particulate solids and total particulate phosphorus associated with a vacuum-assist street cleaner under monthly frequency were about 5.21 and 2.75, and 8.16 and 4.03 percent, respectively. Simulated reductions in total solids and total phosphorus and total particulate solids and total particulate phosphorus associated with a vacuum-assist street cleaner under 3-days per week frequency were about 14.46 and 7.45, and 23.89 and 11.16 percent, respectively.

The regenerative-air street cleaner under monthly conditions estimated reductions of total solids and total phosphorus of about 15.94 and 8.04 percent, respectively. Monthly total particulate solids and total particulate phosphorus precent reductions were about 26.55 and 12.09 percent, respectively. Three-days per week frequency conditions using the regenerative-air street cleaner estimated reductions of total solids and total phosphorus of about 19.12 and 9.26 percent, repectively. Total particulate solids and total particulate phosphorus precent reductions under these conditions were about 32.43 and 13.99 percent, respectively.

Summary and Conclusions

To meet the phosphorus TMDL mandate, the city of Cambridge must reduce its load of phosphorus to the Lower Charles by 65.2 percent. Such a large reduction will require effective management of point and non-point sources. Management of non-point source runoff using structural stormwater control measures will be limited by cost and lack of usable space, placing more emphasis on non-structural SCMs such as street cleaning. The city already employs a progressive street cleaning and curbside yard waste programs to manage debris and maintain overall asthetics between April and December. However, more information about the nature of the material found on street surfaces and the performance of high-efficiency street cleaning technologies on Cambridge streets is needed to assess the potential reductions of phosphorus as the result of street cleaning activtities.

To this end, the USGS, in cooperation with the City of Cambridge, Massachusetts, the Massachusetts Department of Environmental Protection, and the U.S. Environmental Protection Agency, conducted a study to better understand the physical and chemical nature of the material on street surfaces, evaluate the performance of a high-efficiency street cleaner, and estimate potential reductions of total particulate solids and phosphorus loading to the Lower Charles River expected from high-efficiency street cleaning.

Street-dirt samples were collected from six street sections between May 2010 and March 2011 to provide locally-specific information about the accumulation of street-dirt, the washoff of street dirt due to precipitation, and the chemistry of street dirt on three streets representing mostly multifamily residential and three streets representing mostly commercial land-use types. Curb-to-curb (CTC) street-dirt sampling attempted to capture street-dirt distribution and yields as close as possible to the start and end of rain events to determine the percent washed off and the remaining residual load following the storm. Curb-to-curb sampling conducted every day or every other day following a “cleansing” storm provided estimates on the accumulation rate of street dirt. Street-dirt samples were also collected to determine the removal efficiency, or productivity function for a high-efficiency regenerative-air street cleaner. One day each month was dedicated to sampling a single side (SS) of each street 9 ft from the curb before and after street cleaning operations to develop a productivity function for a high-efficiency regenerative-air street cleaner. Samples from the three streets within each land-use types were combined to provide an average value for Cambridge, Massachusetts streets with heavy on-street parking, monthly parking controls, intermediate surface texture, and fair surface condition within multifamily and commercial land use areas.

The median yield of street dirt on multifamily and commercial streets between May and December 2010 was about 575 and 467 lbs/curb-mi, respectively. Including the large amounts observed in March 2011 following the winter season, median yields increased to about 612 and 498 lbs/curb-mi, respectively. Average street-dirt yields on multifamily and commercial land-use streets were about 1.8 times the national average and 2 to 3 times the national average when including the end-of-winter street-dirt yields. Street-dirt yields were greatest during leaf-fall and end-of-winter for multifamily and commercial streets, respectively.

Street-dirt samples were separated into three grain-size fractions: (1) greater than 2 mm, (2) less than 2 mm to greater than 125 µm, and (3) less than 125 µm. About 87 percent of all street-dirt material was greater than 125 µm fraction (or fine sand) regardless of land-use type, which was similar to other studies. However, the greater than 2 mm material was greater on multifamily streets and this difference is attributed to the increased tree density in these areas. In terms of spatial distribution, the long-term nature of on-street parking in Cambridge likely causes a more even distribution of material on the streets compared to areas without on-street parking. About 57 percent of the material was found within 3 ft of the curb, about 74 percent of the material was within 6 ft of the curb and about 95 percent of the material was within 9 ft of the curb.

Median accumulation rate estimates of total street material were about 33 and 23 lbs/curb-mi/day on average for multifamily and commercial land-use streets, respectively. The range of accumulation rates for multifamily streets was between about -43 to 84 lbs/curb-mi/day, and between about -23 to 308 lbs/curb-mi/day on commercial streets. Median accumulation rates for the greater than 2 mm, less than 2 mm to greater than 125 µm, and less than 125 µm grain-size fractions on multifamily streets were about 7, 19, and 7 lbs/curb-mi/day, respectively. Commercial street accumulation rates from coarse to fine were 2, 15, and 6 lbs/curb-mi/day, respectively. Results indicate that multifamily accumulation rates were about 30 percent greater than commercial streets, and street dirt in Cambridge, MA can recover to pre-event yields within 5 to 17 days after washoff or street-cleaning events.

Washoff sample pairs bounded storm events between 0.32 and 1.71 inches and intensities between 0.027 and 0.185 in/hr. Median total washoff for multifamily and commercial land-use types were similar at about 35 and 40 percent, respectively. Washoff by grain-size fraction for all streets were also similar in magnitude and was found to generally increase with decreasing grain size. However, observed net increases were attributed to overland flow and transport of organic debris from source areas other than streets. Net increases following rainfall events were largest in the greater than 2 mm fraction on multifamily streets and in the less than 125 µm fraction on commercial streets.

The percent difference between pre and post regenerative-air street cleaner operation resulted in median removal efficiencies on multifamily streets of about 85 percent and about 79 percent on commercial streets. Removal efficiency decreased with decreasing grain size. Median removal efficiency on multifamily streets were about 92, 83, and 53 percent for the greater than 2 mm, less than 2mm to greater than 125 µm, and less than 125 µm fractions, respectively. Commercial street median removal efficiencies from coarse to fine, were 92, 79, and 51 percent, respectively. Negative values, or net increases in material were occasionally observed within the less than 125 micron fraction. However, this typically occurred on streets with rough and damaged surfaces, and is thought to be a result of the action of the wet gutter broom moving material from inside cracks and holes within the street surface. The regenerative-air street cleaner left a fairly consistant residual yield regardless of land-use type or the magnitude of the initial street-dirt yield of about 103 lbs/curb-mi. Residual loads ranged between 18 and 513 on multifamily streets and 46 and 222 lbs/curb-mi on commercial streets, indicating that this type of regenerative-air street cleaner can begin to be effective at initial street-dirt yields between 18 and 46 lbs/curb-mi.

Median concentrations of organic carbon and phosphorus on multifamily streets were found to be 35 and 29 percent greater, respectively than those commercial streets. Median concentrations generally increased with decreasing grain size, except for organic carbon, Ca, K, Mg, P, and Sr, in results from both land-use types. These constituents had larger concentrations in the greater than 2 mm fraction than in the less than 2 mm to greater than 125 µm fraction. Organic carbon, Ca, and K results from the less than 2 mm to greater than 125 µm were also greater than the less than 125 µm fraction. Median concentrations of organic carbon and total phosphorus on multifamily streets were 91,700 and 700 mg/kg, respectively. Median concentrations of organic carbon and total phosphorus on commercial streets were 60,100 and 500 mg/kg, respectively

The largest constituent masses generally appear within the less than 2 mm and the greater than 125 micron and the less than 125 micron fractions (table 9A and B). Masses from multifamily land-use streets were generally greater than those observed on commercial land-use streets. In particular, the median total masses of Cr, Cu, P and Pb from multifamily streets were about 1.9, 1.4, 5.0, and 12.7 times greater than commercial median total masses, respectively. However, commercial median total yields of Cd, Ni, and Zn were greater than multifamily yields by about 2.0, 1.9, and 1.5 times respectively. Median total masses of organic carbon and phosphorus on multifamily streets found to be 68 and 75 percent greater, respectively than those on commercial streets. About 87 and 75 percent of the mass of phosphorus was found within the two larger grains-size fractions for multifamily and commercial streets, respectively. However, the total phosphorus mass observed within the less than 125 micron fraction on commercial streets was about 47 percent greater than multifamily streets.

The median total accumulation rate of organic carbon for multifamily land use was about 1.43 lbs/curb-mi/day, and ranged between about -11 to 17 lbs/curb-mi/day. The median total organic carbon accumulation rate ranged between about 12 to 4 lbs/curb-mi/day for commercial land use whether Mount Auburn Street data was included or not. Commercial median total accumulation rate of organic carbon was 0.057 lbs/curb-mi/day and increased to 0.067 after omitting data from Mount Auburn Street. Organic carbon accumulation was greatest within the less than 2 mm to greater than 125 µm fraction, followed by the the greater than 2 mm fraction for both land-use types.

The median total accumulation rate of total phosphorus for multifamily land use was about 4.0 x 10^{-4} lbs/curb-mi/day. The largest buildup of total phosphorus by grain-size appears within the less than 2 mm to greater than 125 micron fraction, followed by the less than 125 µm fraction. From coarse to fine, multifamily median accumulation rates of P are about 0.001, 0.004, and 0.010 lbs/curb-mi/day, respectively. The median total accumulation rate of total phosphorus for commercial land use was about 5.0 x 10^{-5} lbs/curb-mi/day. Median commercial build-up rates from coarse to fine are about 5.0 x 10^{-5}, 0.004, and 0.0001 lbs/curb-mi/day, respectively. Removing the results from the street potentially biased low by additional street cleaning only increased the commercial build-up rate of P within the coarse fraction changing the build up rates fro coarse to fine to about 0.0001, 0.004, and 0.0001 lbs/curb-mi/day, respectively.

Washoff from multifamily streets generally appears to be greater than those observed on commercial land-use streets. Median total washoff of organic carbon on multifamily streets is about 59 percent and ranges between -1454 to 95 percent. Commercial median total washoff of organic carbon was similar at about 51 percent and ranged between -268 to 96 percent. The wide range of washoff demonstrates the potential for "wash on" of materials as well as the potential for effective washoff of street materials. Median washoff of organic carbon from multifamily streets was about 42 and 44 percent for the two coarser fractions greater than 125 µm, and about 70 percent for material less than 125 µm. Median commercial washoff of organic carbon by grain-size fraction are about 41, 52, and 79 percent from coarse to fine, respectively. Multifamily median total washoff of phosphorus is about 58 percent and ranged between -1120 to 93 percent. Median washoff by grain size was 39 percent for the two coarser fractions greater than 125 µm, and about 76 percent for material less than 125 µm. Median commercial total washoff of phosphorus was about 48 percent and ranged between about -214 to 99 percent. From coarse to fine commercial washoff was about 34, 51, and 77 percent, respectively.

Constituent mass reductions as a result of regenerative-air street cleaning generally decrease with decreasing grain size, and reductions were slightly less during the spring and summer months, which reflects the relatively lower street-dirt yields available for removal observed between the larger end-of-winter cleanup and autumn leaf-fall loadings. Reductions are greater on multifamily streets for nearly all constituents within the greater than 125 µm fraction, but are less than commercial reductions for 20 of the 33 constituents within the greater than 2 mm fraction, and all other constituents less than 125 µm except for Ag. Net increases following street cleaner operation in the mass of some constituents are seen almost entirely in the less than 125 µm results from multifamily residential streets.

Total phosphorus reductions for multifamily and commercial streets were about 92 and 81 percent, respectively. In terms of grain size, total phosphorus percent reductions on multifamily streets show about 97 percent was removed within the greater then 2 mm fraction, about 92 percent within the less than 2 mm to greater than 125 µm fraction, and about 75 percent within the less than 125 µm fraction. Average percent reduction of total phosphorus on commercial streets from coarse to fine fractions were about 97, 86, and 80 percent, respectively.

A Source Loading and Management Model for Windows version 9.4.0 was applied to a 21.76 acre subcatchment in Cambridge, Massachusetts comprised of commercial, institutional and multifamily land-use types to evaluate the potential reductions of phosphorus. The model performed well compared to runoff and water-quality data collected at the subcatchment outfall in 2000 and street-dirt samples yield data collected in 2010. The subcatchment has a curb-and-gutter drainage system, rooftop runoff represented between 20 to 50 percent of the total runoff simulated at the subcatchment outfall. Street surfaces contributed about 20 percent percent of the total runoff in the model.

Productivity function coefficients for mechanical brush and vacuum-assisted street cleaners were generated by SLAMM based on long-term, on-street parking with parking controls. Regenerative-air street cleaner productivity function coefficients were developed from field data. Simulations based on five years of average climatic conditions yielded potential reductions of total solids of between 2.72 and 5.21 percent for monthly mechanical brush and vacuum-assist street cleaner operation, respectively and about 15.94 percent for the regenerative-air street cleaner. Estimated total phosphorus reductions for monthly use of mechanical brush and vacuum-assisted street cleaners were about 1.41 and 2.75 percent, respectively, and the regenerative-air machine yielded a reduction of about 8.04 percent. Increasing street-cleaning frequency to weekly increased total solids reductions to about 4.21, 9.61, 18.44 percent for mechanical, vacuum-assist, and regenerative-air street cleaner, respectively. Total phosphorus reductions following weekly use of the three technologies were about 2.15, 5.04, and 8.66 percent, respectively. An operational frequency of three times weekly further increased potential reductions of total solids for mechanical, vacuum-assist and regenerative-air to about 6.01, 14.46 and 19.12 percent, respectively. Simulated percent reductions of total phosphorus were about 3.05, 7.45, and 9.26 percent, respectively when streets were cleaned 3 times per week.

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Tables 16 -17

Table 16. Street-dirt composite sample collection dates, start times, locations, intake nozzle widths and resulting masses and yields.

Table 17. Street cleaner removal efficiency composite sample pair collection dates, start times, locations, intake nozzle widths and resulting masses and yields. Precipitation data from Cambridge Department of Public Works gage, 147 Hampshire St, Cambridge, MA.

Appendix Tables 1-4

Table 1. Pre- and post-regenerative-air street cleaner operation seasonal composite samples, locations, and resulting total-recoverable concentrations by grain-size for multifamily land-use streets.

Table 2. Pre- and post-regenerative-air street cleaner operation seasonal composite samples, locations, and resulting total-recoverable concentrations by grain-size for commercial land-use streets.

Table 3. Street-dirt composite sample collection dates, start times, locations, intake nozzle widths and resulting total-recoverable concentrations by grain-size for multifamily streets. Precipitation data from Cambridge Department of Public Works gage, 147 Hampshire St, Cambridge, MA.

Table 4. Street-dirt composite sample collection dates, start times, locations, intake nozzle widths and resulting total-recoverable concentrations by grain-size for commercial streets. Precipitation data from Cambridge Department of Public Works gage, 147 Hampshire St, Cambridge, MA.